PERMAFROST SETTLEMENT CAUSED BY CLIMATE WARMING

IN ALASKA AND THE ESTIMATION OF ITS DAMAGE COSTS

FOR PUBLIC INFRASTRUCTURE

By

Eunkyoung Hong

RECOMMENDED:

Dr. Stephen Colt

Dr. Robert Perkins

Dr. John Walsh

Dr. Sarah Trainor
Advisory Committee Chair

Dr. David Barnes
Chair, Department of Civil & Environmental Engineering

APPROVED:

Dr. Douglas Goering
Dean, College of Engineering & Mines

Dr. Lawrence Duffy
Dean of the Graduate School

August 10, 2012
Date

PERMAFROST SETTLEMENT CAUSED BY CLIMATE WARMING IN ALASKA AND THE ESTIMATION OF ITS DAMAGE COSTS FOR PUBLIC INFRASTRUCTURE

A

THESIS

Presented to the Faculty

Of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

By

Eunkyoung Hong, B.A., M.C.P., M.S.

Fairbanks, Alaska

August 2012

Abstract

Climate models and studies indicate that the changes in the northern latitudes will be serious and accelerated. Climate warming may impact structures in the northern latitudes through permafrost settlement affecting the performance of infrastructure and increasing costs for maintenance.

The material presented is organized in three main chapters. Chapter 1 describes the motivation for the research. Chapter 2 addresses the permafrost settlement hazard in Alaska. I developed the Permafrost Settlement Hazard Index, which considered anticipated climate warming and ecological characteristics which regulate permafrost settlement. I found that the discontinuous permafrost region is at more risk due to permafrost settlement than other regions of Alaska. I also found that the correlation that the areas with high settlement hazard value have higher road maintenance costs. Chapter 3 is an estimate of damage cost caused by permafrost settlement related to climate warming in the field of public infrastructure. I concluded that climate warming may add about $106 million annually from 2010 to 2050 to annual costs for public infrastructure in Alaska. This amount of damage cost is the relative size of damage cost that is caused by climate warming. In order to understand the broader idea of adaptation methods, a case study of Alaska roads for discontinuous permafrost regions is presented in Chapter 4. Some alternative construction methods were chosen as adaptation methods. Then, the comparison of the cost effectiveness of each adaptation method was shown to identify the most economical option when the cost estimation includes the effect of the additional permafrost settlement caused by climate warming. I concluded that pre-thaw method was the most cost effective method. I also recommended Air-Cooled Embankment on a condition that coarse rocks are available to create a convection cell. Chapter 5 summarizes the research and indicates possibilities for future research directions.

I employed an interdisciplinary approach combining engineering knowledge with environmental impact assessments, utilizing economic tools in estimating damage costs, and analyzing the cost effectiveness of adaptation options to climate induced permafrost settlement. Nevertheless, this interdisciplinary analysis was not intended as a civil engineer design but intended for these economic estimates.

Table of Contents

List of Figures

List of Tables

Chapter 1 Historical Perspective and Overview of Research

The global average surface temperature has increased especially since the mid-20th century (IPCC, 2007) and average annual temperatures in Alaska have increased 1.7 °C since 1949 (Alaska Climate Research Center, 2012). Moreover, scientists and many climate models project that changes in the Arctic areas will be accelerated (ACIA, 2004, Nelson et al., 2001, U.S. Arctic Research Commission Permafrost Task Force, 2003, ACIA, 2005, Nelson et al., 2002, Dey, 2003). Permafrost temperatures over the Arctic have increased during the past few decades and the depth of the active layer is also increasing in many regions (ACIA, 2004, Romanovsky and Osterkamp, 2001). Permafrost degradation is defined as "a naturally or artificially caused decrease in the thickness and/or areal extent of permafrost (IPCC, 2007)." Over the next 100 years, permafrost temperatures are projected to increase with permafrost degradation expected to occur over 10-20% of the current permafrost area (Callaway et al., 1999, ACIA, 2004). These results cause more considerable concern about the future of permafrost and impacts associated with warming on infrastructure.

Current economic activities, such as mineral exports, fisheries and tourism, in the Arctic depends on the limited transportation infrastructure (National Research Council Committee on Climate Change and U.S. Transportation Research Board Division on Earth and Life Studies, 2008). The effects of warming permafrost can disrupt human infrastructure such as roads, bridges and buildings (U.S. Arctic Research Commission Permafrost Task Force, 2003, Nelson et al., 2001, Romanovsky and Osterkamp, 2001, ACIA, 2005, Nelson et al., 2002).

Problems associated with permafrost thaw and its adverse impact on foundations and structures have already been discussed in specialist literature and research papers (U.S. Arctic Research Commission Permafrost Task Force, 2003, Romanovsky and Osterkamp, 2001, Nelson et al., 2001, ACIA, 2005, Nelson et al., 2002). Existing infrastructure that was built on permafrost could be destabilized requiring substantial maintenance, rebuilding and reinvestment (ACIA, 2004, U.S. Arctic Research Commission Permafrost Task Force, 2003, Fortier et al., 2011). Some researches point out that numerous infrastructure failures in the Arctic have not been caused by permafrost warming, but rather by poor design, construction activity, the structure itself (radiation and snow accumulation) and poor maintenance (Shur and Goering, 2009, Instanes, 2003). In addition, the disturbance of the road surface caused by construction activity often increases the mean annual surface temperature and subsequent permafrost degradation (Goering, 1998). Nevertheless, thawing of ice-rich permafrost has been identified as a primary problem for infrastructure and climate warming will cause additional permafrost thaw (Osterkamp et al., 1998).

Accordingly, my dissertation researched current permafrost settlement hazard and future permafrost settlement hazard in Alaska in the context of climate change. Nelson et al. (2001) introduced the concept of hazard zonation in the Arctic and presented a hazard zone map for the Northern Hemisphere. Their map was based on calculations by Anisimov and Nelson (Anisimov and Nelson, 1997) under the ECHAM1, a general circulation model. They also used information of soil properties, permafrost distribution and ice content. However, Nelson et al. (2001) did not consider other ecological characteristics such as vegetation and organic layer which also affect the stability of permafrost. In addition, the results did not provide any details about the permafrost hazard in a specific area since they covered the entire Northern hemisphere. Therefore, my dissertation researched the permafrost settlement hazard of Alaska in the context of climate warming, focusing on ecosystem characteristics which also affect permafrost settlement.

I also estimated damage costs caused by permafrost settlement under the current temperature projection condition. In particular, I focused on the public infrastructure in Alaska. Larsen et al. (2008) did preliminary research, estimating the future costs for Alaska public infrastructure at risk from the climate change. However, I developed the database and methodology moving beyond limitations of the preliminary study. The estimation in my study dealt with the whole cost required during the life cycle of the infrastructure, through the Life Cycle Cost Analysis (LCCA), while Larsen et al. (2008) considered only replacement costs. Larsen et al. (2008) set up assumptions about thaw settlement of facilities on permafrost for each permafrost area, ultimately to draw the information of reduction in service life for two climatic variables (temperature and precipitation). However, I estimated the service life of the structures, which is the lifespan of the structure, instead of providing assumptions to predict it. Also, instead of showing total cost from now to 2050, I presented the cost which would be required annually to build and maintain by the end of service life.

Finally, I investigated adaptation options to decrease the damage costs. I presented a case study of Alaska roads in discontinuous permafrost regions. I introduced some adaptation methods for Alaska roads and showed the cost effectiveness of each adaptation method.

In Chapter 2, I describe the permafrost settlement hazard in Alaska. I obtain the statewide Permafrost Settlement Hazard Index (PSHI) map as a product. Through statistical analysis, I find that the discontinuous permafrost region is at more risk due to permafrost settlement than other regions. In addition, using the PSHI and the expenditure data used for road maintenance provided by the Alaska DOT, I find the correlation that the areas with high settlement hazard value have required more costs for road maintenance.

In Chapter 3, I present the result of damage estimates. I estimate damage costs of public infrastructure in Alaska caused by climate change by 2050. I conclude that the climate change could add $106 million (7.5% of the total annual cost) annually to annual costs for public infrastructure from 2010 to 2050.

In Chapter 4, I review three alternative construction methods (pre-thaw, Air-Cooled Embankment (ACE), and thermosyphon) as adaptation methods. Pre-thaw is used to thaw unstable permafrost layer prior to construction and ACE is a method that allow air convection using coarse rocks. Thermosyphon refers to a heat transfer device. We make recommendations on the best adaptation method for Alaska roads based the economic evaluation. I estimate that the pre-thaw method is the most cost effective. I also conclude that ACE is still desirable depending on site places where competent rock is available. Thermosyphon is not recommendable from an economic viewpoint.

In the final Chapter, I summarize the results of the studies presented herein and discuss the broader implications of my findings.

1.1. Reference Cited

ACIA (2004) Impacts of a warming Arctic: Arctic climate impact assessment, Cambridge University Press.

ACIA (2005) Arctic climate impact assessment, Cambridge University Press.

Alaska Climate Research Center (2012) Temperature Change in Alaska. In Alaska Climate Research Center (Ed.). Geophysical Institute, University of Alaska Fairbanks.

Anisimov, O. A. & Nelson, F. E. (1997) Permafrost zonation and climate change: results from transient general circulation models. Climatic Change 35, 241-258.

Callaway, D., Eamer, J., Edwardsen, E., Jack, C., Marcy, S., Olrun, A., Patkotak, M., Rexford, D. & Whiting, A. (1999) Effects of climate change on subsistence communities in Alaska. Assessing the Consequences of Climate Change for Alaska and the Bering Sea Region, 59-73.

Dey, P. (2003) Analytic hierarchy process analyzes risk of operating cross-country petroleum pipelines in India. Natural Hazards Review 4, 213-221.

Fortier, R., LeBlanc, A.-M. & Yu, W. (2011) Impacts of permafrost degradation on a road embankment at Umiujaq in Nunavik (Quebec), Canada. Canadian Geotechnical Journal 48, 720-740.

Goering, D. J. (1998) Experimental investigation of air convection embankments for permafrost-resistant roadway design. Seventh International Conference. Collection Nordicana, No 55, Whitehorse, Canada, p.319-326.

Instanes, A. (2003) Climate change and possible impact on Arctic infrastructure. Permafrost: Proceedings of the Eighth International Conference on Permafrost. A.A. Balkema.

IPCC (2007) Climate change 2007 : the physical science basis : contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Larsen, P. H., Goldsmith, S., Smith, O., Wilson, M. L., Strzepek, K., Chinowsky, P. & Saylor, B. (2008) Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environmental Change-Human and Policy Dimensions 18, 442-457.

National Research Council. Committee on Climate Change & U.S. Transportation Research Board Division on Earth and Life Studies (2008) Potential impacts of climate change on U.S. transportation, Washington, D.C., Transportation Research Board.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2001) Subsidence risk from thawing permafrost - The threat to man-made structures across regions in the far north can be monitored. Nature 410, 889-890.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2002) Climate change and hazard zonation in the circum-Arctic permafrost regions. Natural Hazards 26, 203-225.

Osterkamp, T. E., Esch, D. C. & Romanovsky, V. E. (1998) Permafrost, In: G. Weller and P.A. Anderson (Eds.) Implications of Global Change for Alaska and the Bering Sea Region, Proceedings of a Workshop, University of Alaska Fairbanks, 3–6 June.

Romanovsky, V. & Osterkamp, T. (2001) Permafrost: changes and impacts. In R. Paepe & V. Melnikov (Ed.) Permafrost response on economic development, environmental security and natural Resources. Dordrecht, Netherlands: Kluwer Academic Publishers, 297-315.

Shur, Y. & Goering, D. (2009) Climate change and foundations of buildings in permafrost regions. Permafrost Soils, 251-260.

U.S. Arctic Research Commission Permafrost Task Force (2003) Climate change, permafrost, and impacts on civil infrastructure, Special Report 01-03, U.S. Arctic Research Commission, Arlington, Virginia.

Chapter 2 Permafrost Settlement Hazard Related to Climate Warming in Alaska and its Impact on Public Infrastructure [1]

2.1. Abstract

Permafrost temperatures have increased in Alaska since the 1960s and many impacts of climate warming are associated with permafrost thaw. Increases in permafrost temperature may result in thaw settlement and significant damage to public infrastructure. The purpose of this research is to examine regions at risk from permafrost settlement related to climate warming in Alaska and evaluate the relationship between the permafrost settlement hazard and maintenance costs for Alaskan roads. In order to examine the correlation, we developed the Permafrost Settlement Hazard Index (PSHI) by analyzing anticipated climate warming and the ecological characteristics that regulate permafrost settlement. We found that the discontinuous permafrost region is at more risk due to permafrost settlement than other regions of Alaska. Moreover, the connection between PSHI and public road maintenance cost shows that the areas with high PSHI values require more expenditure for maintenance. Projections of future permafrost settlement indicate greatest risk in northern Alaska.

2.2. Introduction

Average annual temperatures in Alaska have increased 1.7°C since 1949 (Alaska Climate Research Center, 2012) and climate models indicate continued rapid warming in northern latitudes (ACIA, 2004, Nelson et al., 2001, U.S. Arctic Research Commission Permafrost Task Force, 2003, Dey, 2003, Nelson et al., 2002, ACIA, 2005). Many consequences of climate warming in the high northern latitudes are associated with permafrost (Nelson et al., 2002). Permafrost is soil that remains at or below 0°C for two or more consecutive years (Washburn, 1980, Brown et al., 1973). Climate warming affects the temperature of the frozen ground, the

[1] Hong, E., Perkins, R. & Trainor, S. Permafrost settlement hazard related to climate warming in Alaska and its impact on public infrastructure. Prepared for submission to Arctic.

depth of seasonal thawing (ACIA, 2004, Romanovsky and Osterkamp, 2001, Osterkamp, 2007), and the patterns of formation and stability of permafrost (Shur and Jorgenson, 2007). Permafrost temperatures in many Arctic regions have increased during the past few decades (ACIA, 2004, Romanovsky and Osterkamp, 2001) and mean annual ground surface temperatures along a north–south transect in Alaska have increased by 2.5 °C since the 1960s (Osterkamp, 2005, Romanovsky and Osterkamp, 2000, Osterkamp and Romanovsky, 1999).

Due to its thermal interaction with ecosystem characteristics such as topography, surface water, groundwater, soil properties, vegetation, and snow, permafrost does not respond directly to temperature change (Jorgenson et al., 2010, Smith and Riseborough, 1996, Zhang et al., 1997). Rather, ecosystem characteristics regulate permafrost temperature and the depth of seasonal thaw (Jorgenson et al., 2010, ACIA, 2005). Therefore, disturbances of vegetation and soil by human activity and wildfire contribute to permafrost degradation (Myers-Smith et al., 2008, Jorgenson et al., 2010, Shur and Jorgenson, 2007). In addition, heat from groundwater may advance permafrost degradation (Jorgenson et al., 2001) and removal of the insulative surface snow by wind also affects permafrost degradation (Zhang et al., 1997).

Nelson et al. (2001) provide a geographic overview of the hazard potential associated with permafrost thaw in the Arctic and project that much of the existing infrastructure in potential high hazard areas could be affected by thaw subsidence under the conditions of climate warming. They calculated a settlement index by multiplying the relative increase of active layer thickness by the volumetric proportion of near- surface soil containing ground ice. However, Nelson et al. (2001) did not consider other ecosystem characteristics that influence permafrost thaw. Further, because their study surveyed the entire Northern Hemisphere, its results did not provide detailed information about the permafrost hazard in a specific area. A few years later, Smith et al. (2004) examined the sensitivity of permafrost to climate warming in Canada; however, their research provided limited data on permafrost settlement hazard in Alaska. Therefore, the research presented here specifically examines permafrost settlement hazard in Alaska, concentrating on the factors that affect permafrost settlement, such as ground ice, snow, and soil, and creating a Permafrost Settlement Hazard Index (PSHI) for Alaska. Therefore, this study was designed to identify Alaskan areas at risk from permafrost settlement.

Warming permafrost and the associated increase in depth of the summer thawed layer (the active layer) can disrupt infrastructure such as roads, bridges, and buildings (U.S. Arctic Research Commission Permafrost Task Force, 2003, Nelson et al., 2001, Romanovsky and Osterkamp, 2001, ACIA, 2005). Problems associated with permafrost thaw and its adverse impact on building foundations and other infrastructure are well documented (Nelson et al., 2001, Larsen et al., 2008, Nelson et al., 2002, Williams, 1995, U.S. Arctic Research Commission Permafrost Task Force, 2003, ACIA, 2005). Nevertheless, permafrost thaw can occur irrespective of climate warming. For example, the disturbance of the road surface caused by construction activity often increases the mean annual surface temperature and subsequent permafrost degradation (Goering, 1998). Nevertheless, thawing of ice-rich permafrost has been identified as a primary problem for infrastructure and climate warming will cause additional permafrost thaw (Osterkamp et al., 1998). Larsen et al., (2008) presented one model for estimating increased cost to public infrastructure from climate related permafrost settlement in Alaska. In this study, in order to recognize the impact of permafrost settlement related to climate warming on maintenance cost, the relationship between the PSHI and maintenance costs of the public infrastructure was evaluated. Due to limited data available for Alaska's infrastructure maintenance costs, however, we limit our analysis to the maintenance cost for public roads only.

Figure 2.1 shows the distribution of permafrost in Alaska. Permafrost regions are divided into four distinct classes based upon the estimated percentage of the ground that is underlain by frozen ground: continuous (> 90%); discontinuous (50 - 90%); sporadic (10 - 50%); and isolated patches (0 - 10%) (Zhang et al., 1999). In Alaska, 84% of the state is underlain by permafrost - 33% continuous, 39% discontinuous, 12% sporadic, and 1% isolated permafrost. Some studies indicate that continuous permafrost and discontinuous permafrost respond differently to climate warming (Nelson et al., 2001, Romanovsky and Osterkamp, 2001, ACIA, 2005). It has been suggested that the reaction in discontinuous permafrost regions to temperature increases may be more crucial because its temperature is only a few degrees below the freezing point (Nelson et al., 2002, Jorgenson et al., 2001, ACIA, 2005). Nelson et al. (2001) mapped the impacts associated with thawing permafrost showing that high and moderate potential for permafrost hazard is concentrated in central and northern Alaska which corresponds to much of the discontinuous permafrost area in Figure 2.1.

Using the PSHI, information about permafrost distribution in Alaska, and expenditure data used for road maintenance (provided by the Alaska Department of Transportation and Public Facilities (AK DOT&PF)), we tested the following two hypotheses:

The discontinuous permafrost region of Alaska is more at risk of permafrost settlement than the continuous permafrost region.

The areas with high permafrost settlement hazard value (PSHI) require greater maintenance costs.

2.3. Method

2.3.1. Permafrost Settlement Hazard Index (PSHI)

The PSHI is based on the concept of a Sensitivity Index for Global Sea-Level Rise on Canadian Coasts developed by Shaw et al. (1998). The method for this Sensitivity Index (SI) measures seven physical variables related to sea-level rise and identifies those regions in which the effects of sea-level rise are greatest (Shaw et al., 1998). Adapting the SI method to Alaska and the parameters of our research, we identified six ecosystem characteristic variables that affect permafrost settlement in Alaska. Table 2.1 lists these variables, their data sources, and the resolution of the maps utilized. We calculated the PSHI by combining the risk value of each variable using the Geographic Information System (GIS) spatial analysis techniques, including overlay analysis.

The risk value of each variable was given a range from one to five: one representing the lowest risk of contribution to permafrost settlement and five representing the highest risk. The risk value of each variable was assigned based on classification of each variable and its relative significance to the permafrost settlement (e.g., classification of high, moderate, variable, low, and unfrozen for *ground ice*), depending on the information of the maps used in the GIS and literature review. Finally, the assigned risk values were combined with weights calculated from the Analytic Hierarchy Process (AHP) (Saaty, 2008) (See Section 2.3.1.2).

2.3.1.1. Variables

Numerous ecosystem characteristics contribute to permafrost formation and degradation and regulate permafrost temperature and thaw depth (Jorgenson et al., 2001, Jorgenson et al., 2010, ACIA, 2005). Due to limited data availability in Alaska, we considered the following six characteristics as variables: ground ice volume, air temperature, soil texture, snow depth, vegetation, and organic content of soil.

The melting of *ground ice* affects the strength of frozen soils and results in loss of permafrost stability (Andersland and Ladanyi, 2004, Smith et al., 2004). Moreover, the ground ice content in the area also determines the climate-induced changes in permafrost (Nelson et al., 2002). Where permafrost contains massive ground ice or is ice-rich, extensive thaw settlement may be expected (Romanovsky and Osterkamp, 2001, Smith et al., 2004, Doré, 2005). The thawing of ice-rich soils causes subsidence and creates depressions in the ground surface (Jorgenson et al., 2010, Romanovsky and Osterkamp, 2001) and/or stresses in the structures on that ground surface. Jorgenson et al. (2008) classifies ground ice content as high, moderate, variable, low, and unfrozen. Due to the potential effect of temperature increase on ground ice content, we assigned areas that have a "high" volume of ground ice a higher (larger) value than those with "unfrozen" ground.

Air temperature is another indicator of permafrost and is a reliable tool to estimate ground temperature (Smith et al., 2004). Permafrost areas where ground temperatures are greater than -2°C have a high potential for permafrost thaw (Smith et al., 2004). Williams (1995) states that permafrost starts to thaw from the surface and all permafrost will disappear when the mean annual temperature of ground surface rises above 0°C. Smith and Riseborough (2002) explain that a mean annual air temperature (MAAT) greater than −2.0°C represents the threshold for the disappearance of permafrost in mineral soils. It must be noted that Williams (1995) bases his estimates on ground surface temperature, whereas Smith and Riseborough (2002) base their estimates on air temperature.

To determine air temperature, we used the 2009 Alaska historical temperature dataset which was compiled by the Scenario Network for Alaska and Arctic Planning (SNAP). The SNAP dataset (Scenarios Network for Alaska and Arctic Planning (SNAP), 2010) relies on MAAT-based information collected by the Climate Research Unit (CRU) of the University of East Anglia. It was necessary to determine a reasonable temperature threshold in MAAT where permafrost becomes vulnerable to temperature change and for simplicity in calculation, we rounded the MAAT off to the nearest whole number. Since the studies of Smith and Riseborough (2002) as well as Williams (1995) provide a threshold temperature based on different temperature standards (air or ground), it was challenging to set a single threshold temperature in MAAT. So, we determined a threshold range of −4.0°C to −1.0°C rather than a single threshold temperature. In addition, because permafrost is steadily frozen at the lower temperature, we assigned relatively lower risk values when MAAT was below the threshold temperature range. In addition, the risk value decreases as the temperature increases when MAAT is above the threshold range. This is because permafrost is rare in those areas. In summary, we assigned an increased risk value until the temperature threshold range, which is the highest risk value, then, assigned a decreased risk value as the temperature increases. Such risk value assignments are symmetric relative to the temperature threshold range (see Figure 2.2).

Soil texture affects soil moisture and thermal properties (Jorgenson et al., 2010, Shur and Jorgenson, 2007); for example, gravelly soils have a tendency to be well-drained while fine soils tend to be poorly drained. The distribution of ground ice is strongly affected by soil texture. Fine-grained material such as silts and clayey silts or peat are generally ice-rich, thus, they give rise to larger thaw settlements (Smith et al., 2004, Andersland and Ladanyi, 2004). Since we also examined organic soil independently as one of the variables focusing on thermal conductivity, the risk value of soil texture was assigned based on the possibility of ground ice soil. Risk values were assigned from 1 to 5 corresponding to the delineation of the geological features and soil texture as outlined in Jorgenson et al. (2008). Therefore, soil with silty composition or fine-grained material was given a higher value than soil of gravelly composition.

Snow has low thermal conductivity and is a strong, effective insulator that limits the heat transfer between atmosphere and ground (Romanovsky and Osterkamp, 2001, Smith et al., 2004, Camill, 2005, Zhang, 2005). In addition, snow has high albedo and emissivity that cools the surface. However, snow has a high degree of absorptivity and takes in more energy, resulting in a warming of the snow-covered surface (Zhang, 2005). The overall impact of snow depth depends on the duration, accumulation and melting processes of seasonal snow cover (Smith et al., 2004, Zhang, 2005). Thus, it is a challenge to attempt to quantify the effect of snow on permafrost. Nevertheless, many studies point out that increased snow cover may result in a significant permafrost temperature increase. Osterkamp et al. (2009) and Jorgenson et al. (2001) show that the increase of snow cover in Alaska has contributed to permafrost degradation.

We used Jorgenson et al. (2008)'s mean snow depth calculation that measured the October to April snow depth data incorporating ground properties, vegetation cover, and their effect on heat turnovers through the snow (Jorgenson et al., 2008). There may be information overlap with variables especially as to geological features; however, we used this data because there was no alternative source material for snow depth in Alaska. The effect of snow on soil temperatures is nonlinear, but current knowledge on the effect of snow depth on ground temperature is incomplete (Jorgenson et al., 2001). Therefore, we broadly grouped the snow depth in numerical ranges and provided relative risk values. Areas with thick snow cover were given a higher value than those with little snow cover because research has shown that the increase in snow cover contributes to permafrost degradation (Osterkamp et al., 2009, Jorgenson et al., 2001).

Permafrost forms independent of *vegetation* in cold areas (Shur and Jorgenson, 2007). However, vegetation has an important effect on permafrost by insulating and making it resilient to increased air temperatures (Jorgenson et al., 2010). Vegetation also regulates soil temperature by dampening the impact of air temperature changes on permafrost (Shur and Jorgenson, 2007). Jorgenson et al. (2001), through their study of Tanana Flats in central Alaska, determined the relationships between permafrost degradation and vegetation types. We assigned a risk value of the specific vegetation type based on the results of the studies in Jorgenson et al. (2010 and 2001). We assigned high risk values to barren land or tundra while giving low risk values to tall forest areas.

The organic layer of the soil plays an important role in regulating permafrost temperature (Jorgenson et al., 2010, ACIA, 2005). Peatlands, through their large thermal offsets, often keep the southernmost permafrost in regions with temperatures as warm as +1.0 to +1.5 °C MAAT. The organic layer of soil tends to be poorly drained and have higher thermal conductivity in winter than in summer. This difference results in rapid heat loss in winter and slower heat penetration in summer and accounts for the thermal offset between the ground surface and the permafrost table (Romanovsky and Osterkamp, 1995). On the other hand, organic and fine-grained materials generally have high structural ice contents, which cause permafrost to thaw and finally cause the construction foundation(s) above permafrost to be unstable (Smith et al., 2004). Since we considered ground ice volume and soil texture as separate variables in this study, we focused only on the thermal conductivity and offset properties of organic soil. Organic soil is often termed "peat," "bog," "fen," "moor," and "muskeg" (Galloway et al., 1999, Gore, 1983). Low risk values were assigned to soil with organic material and high risk values were given to soil containing no organic material.

2.3.1.2. Weighted Index

The permafrost stability caused by climate warming depends on complex interactions among ecological components (Jorgenson et al., 2010, Jorgenson et al., 2001). However, there is still limited understanding of the degree to which each ecological factor contributes to permafrost degradation. Therefore, in this study, we estimated weights for the PSHI through the analytic hierarchy process (AHP) (Saaty, 2008). The AHP is a method of measurement that has numerous practical advantages because it allows the researcher to include both tangible and intangible factors used in science and mathematics in a realistic and justifiable way (Saaty, 2008). The AHP is based on the following three principles: decomposition, comparative judgment, and synthesis of priorities (Dey, 2003). For example, the researcher breaks down the problem into separate elements, ranks the elements according to relative importance, and synthesizes the importance of each (Pineda-Henson et al., 2002).

Table 2.2 shows the rank of variables we set up for the comparative judgment. Serious permafrost settlement depends on ice content (Nelson et al., 2001, Doré, 2005). We considered ground ice to be the most significant factor in permafrost settlement because ground ice is a precondition of permafrost settlement (Kääb and Haeberli, 2001). Extensive thaw settlement may be expected where permafrost contains massive ground ice or is ice-rich (Romanovsky and Osterkamp, 2001, Smith et al., 2004, Doré, 2005). Next, as most permafrost studies mention temperature as the main factor in determining the occurrence, degradation, and characteristics of permafrost (Smith et al., 2004, Osterkamp and Romanovsky, 1999, Andersland and Ladanyi, 2004), we ranked temperature as the second ranking variable in permafrost settlement. Though the effect of snow cover has usually been cited as the principal cause of permafrost temperature increase (Osterkamp et al., 2009, Smith and Riseborough, 2002, Osterkamp and Romanovsky, 1999, Osterkamp, 2005), in this study, we accorded greater importance to soil texture because of its influence on ice volume (Smith et al., 2004, Andersland and Ladanyi, 2004). In some surface temperature models, organic soil condition follows snow cover and vegetation (Camill, 2005). We adopted Camill's findings when ranking importance of snow cover, vegetation and organic condition. Finally, in the ranking of ecosystem variables for this study, we judged ice volume as most important followed by temperature, soil texture, snow cover, vegetation and organic soil.

Then, we calculated weights for each PSHI variable according to the AHP process following (Saaty, 2008): According to the AHP process, paired variables were compared and assigned equal, moderate, strong, very strong, or extreme importance. These judgments were translated into numerical values on a scale of 1 to 9 as shown in Table 2.3. Table 2.4 shows the combination of pairs of all six variables and our judgment of importance rank of variables. Based on the importance rank of variables (Table 2.2) and the scale of relative importance for pairwise comparisons (Table 2.3), we assigned the intensity of importance for each pair from 3 to 9. Table 2.5 displays in an array-type graph of the relative importance and inverses entered in the transpose position. Table 2.6 is the matrix form of Table 2.5. We computed the sum of each column and then divided each column by the corresponding sum to normalize the weights (See Table 2.7). Then, by averaging the values of each row of normalized weights in Table 2.7, we calculated weights for each PSHI variable. Table 2.8 shows the variable weights to be used in the PSHI.

Therefore, the permafrost hazard value of each pixel in the GIS was calculated using the following equation:

Equation 1

$$PSHI = A * 0.44 + B * 0.27 + C * 0.14 + D * 0.08 + E * 0.04 + F * 0.03$$

Where,

A: Risk value of ground ice

B: Risk value of temperature

C: Risk value of soil texture

D: Risk value of snow depth

E: Risk value of vegetation

F: Risk value of organic soil

2.3.2. Maintenance Cost Analysis

Maintenance cost analysis examines the relationship between the weighted PSHI values and actual annual Alaskan road maintenance expenses, using the average of Alaskan road maintenance costs from 2005 to 2010. We hypothesized that regions with high PSHI required more maintenance costs. To determine maintenance costs, we used public road maintenance costs (expenditures). We obtained the annual maintenance expenditure data for the years from 2005 to 2010 and mile-point information from AK DOT&PF (Alaska Department of Transportation and Public Facilities (AKDOT), 2010). This data covers 5,555 miles and 1,048 road segments of Alaskan roads.

Maintenance activities that might result from permafrost degradation were identified and isolated from total road maintenance expenditures (See Table 2.9). However, including expenditure for these activities in non-permafrost areas in our maintenance cost analysis, which are irrelevant to permafrost settlement or degradation, might obscure the relationship between road maintenance cost and permafrost settlement hazard. Thus, we excluded areas with a low PSHI; only areas with a PSHI above 3.0 were included in the analysis. Two-sample nonparametric test was used to test the relationship between the weighted PSHI values and actual annual Alaskan road maintenance expenses. Therefore, areas with risk of permafrost settlement were divided into two groups: Group A (PSHI 3.0-3.9) and Group B (PSHI 4.0-4.9).

According to Connor and Gentry (1982), the Alaska Highway System is sub-divided into eight road types: 4-lane paved urban routes, 4-lane paved rural routes, 2-lane paved urban routes, 2-lane paved rural primary routes, 2-lane paved rural secondary routes, 2-lane gravel secondary routes, minimum service routes («20 ft. gravel surface), and 2-lane local routes (paved or unpaved) (Connor B. and Charles W. G., 1982).

The AK DOT &PF classifies roads into the following twelve (12) categories: rural interstate, rural local road, rural major collector, rural minor arterial, rural minor collector, rural other principal arterial, urban collector, urban interstate, urban local road, urban minor arterial, urban other principal arterial, and unclassified (Alaska Department of Transportation and Public Facilities (AKDOT), 2010). The AK DOT &PF road data does not contain lane information for roads. Rather, the AK DOT &PF data gives the mile information for each road repaired. Therefore, for comparative purposes, cost was computed as $/mile. Cost difference according to road category was also tested. A nonparametric test showed that there is no systematic cost difference associated with different road categories. As a result, $/mile was used for roads regardless of lane information and road category.

Construction cost can be inflated by cost increases in materials, fuel, labor and other related factors (Mclawhorn, 2006). To avoid these inflated costs, we adjusted the construction cost data using the Construction Cost Indices (CCI) compiled by the Federal Highway Administration (FHWA) and individual states to calculate an annual CCI that includes the unit costs of seven typical construction bid items (Washington State DOT, 2011). Alaska does not calculate a CCI, so we used the closest state with a published CCI, State of Washington's CCI (see Table 2.10). In order to compare the 2005–2010 maintenance costs with the current PSHI, CCI was used to adjust the maintenance costs for each year to 2010 dollars. We then averaged the adjusted costs of each year (2005-2010).

In order to link road maintenance cost to the PSHI, we input the average of the adjusted costs of each year (2005-2010) in GIS format Alaska road map. Then, we overlaid the map of the Alaska roads including the average of the adjusted costs, with the PSHI map.

2.3.3. Statistical Analysis

We hypothesized that 1) The discontinuous permafrost region of Alaska is more at risk of permafrost settlement than the continuous permafrost region and; 2) The areas with high permafrost settlement hazard value (PSHI) require greater maintenance costs. To test these hypotheses, we used nonparametric statistics, which is used to compare two or more independent groups when there is no assurance that the observed data follow a normal distribution (Elliott and Woodward, 2010). The Wilcoxon rank-sum test (also called the Mann-Whitney Test) was used to determine whether there were significant differences (values) between two samples specifically the distribution of X-measurements (PSHIs) in population A (continuous region) and X-measurements (PSHIs) in population B (discontinuous region) and; the distribution of X-measurements (average of maintenance costs from 2005 to 2010) in population A (PSHI 3.0-3.9) and that of the same X-measurements in population B (PSHI 4.0-4.9).

A P-value is commonly used to determine whether the difference between two unpaired distributions is statistically significant. In this study, P-values were calculated in two cases: the correlation between PSHI and permafrost region and the correlation between PSHI and maintenance costs.

2.3.3.1. PSHI Test

PSHI between discontinuous permafrost and continuous permafrost were compared to identify Alaskan area more at risk from permafrost settlement. We assumed that the distribution of X-measurements (PSHIs) in population A (continuous region) would be the same as those (PSHIs) in B (discontinuous region), which we would write symbolically as

Ho: A = B

If we expected that the distribution of B would shift to the right of distribution A as in Figure 2. 3, we would write this as

H1: A < B

In the above case, if the calculated p-value with a null hypothesis (H0) is less than a specified alpha level (in this study we used 0.01), we reject the null hypothesis (H0). We can conclude that the two population medians substantially differ (Pappas and DePuy, 2004), thus, alternative hypothesis H1 is accepted.

2.3.3.2. Maintenance Cost Test

Non parametric statistics were used to find the relationship between PSHI and maintenance cost because there was no assurance that this cost data follow a normal distribution. We hypothesized that the region with high PSHI required more maintenance costs. Therefore, we tested the hypothesis that the distribution of X-measurements (average of maintenance costs from 2005 to 2010) in population B (roads having a PSHI 4.0-4.9) shifted to the right of that in population A (roads having a PSHI 3.0-3.9). If the p-value is less than the specified alpha level, then there is evidence to suggest that the two population medians differ, thus, the alternative hypothesis is accepted (Pappas and DePuy, 2004).

2.4. Results

2.4.1. PSHI

The PSHI was developed to enable analysis of anticipated permafrost settlement caused by climate warming. Figure 2.4 maps the results of our PSHI findings. The numbers on the map are rounded PSHI values; a higher number means a greater likelihood of permafrost settlement hazard. Dots on the map represent the locations of the Alaskan cities and villages. By overlaying the PSHI map with the locations of cities and villages, the hazard value for each locale can identified. Also, by overlaying the map of permafrost distribution (see Figure 2.1) with the PSHI map (see Figure 2.4), permafrost distribution and PSHI values can be plotted for certain areas.

We initially hypothesized that the discontinuous permafrost region would be more at risk because of permafrost settlement than the continuous permafrost region. In order to test the hypothesis, we attempted to prove that the distribution of X-measurements (PSHIs) in population B (discontinuous region) is shifted to the right of that in population A (continuous region). Figure 2.5 shows the probability of PSHI by each group when we assumed same data count numbers to each group. This Figure 2.5 indicates that each group (Group A and B) has a probability peak in a different PSHI range.

In our analysis, the p-value under the null hypothesis suggesting A=B was computed to be $< .0001$. This leads to rejection of the null hypothesis that there is no statistical difference in A and B. As the result is less than 0.0001, there is very strong evidence of a difference at $\alpha=0.01$ thereby accepting the alternative hypothesis that the discontinuous permafrost region would be more at risk due to permafrost settlement than the continuous permafrost region.

2.4.2. PSHI Map and Maintenance Cost

In order to link road maintenance cost to the PSHI, we overlaid the map of the Alaska roads including the maintenance cost with the PSHI map (See Figure 2.6).

As shown in Figure 2.6, there are few roads in the high risk (Group B) permafrost regions. As a result, there are a small number of cost data points for Group B. We obtained 84 pieces of data for Group B (roads having a PSHI 4.0-4.9) whereas we obtained 370 data pieces for Group A (roads having a PSHI 3.0 -3.9). Due to this large variability, we investigated probability by cost ranges (by $5000/mile) within each group.

Figure 2.7 shows the probability of maintenance costs by PSHI group. For example, 81% of roads in Group A have required maintenance cost under $5000/mile, whereas 56% of roads in Group B have required maintenance cost under $5000/mile. Thus, it is more likely that roads located in Group B have high maintenance costs.

Table 2.11 shows examples of average maintenance cost/mile from the AK DOT&PF 2005-2010 records for the same category of roads ("urban collector" in AK DOT&PF records). The three examples in Table 2.11 show the tendency that the average maintenance cost per mile increases as the average PSHI value increases.

Therefore, we tested the hypothesis that the distribution of X-measurements (average of maintenance costs from 2005 to 2010) in population B (roads having a PSHI 4.0-4.9) is shifted to the right of that in population A (roads having a PSHI 3.0 -3.9). The non-parametric test showed a statistically significant result with p-value < 0.0001, accepting the alternative hypothesis that the areas with high PSHI have required higher maintenance costs than the areas with low PSHI.

2.5. Discussion and Limitations

2.5.1. PSHI

To verify our calculated PSHI results, we tested the result using alternative importance ratings for each pair of ecosystem variables listed in Table 2.4. For example, initially, we assigned 3 to the importance of ground ice volume as compared to temperature (see Table 2.4). We also gave a value of 4 to ground ice volume while keeping the importance rank of variables constant (see Table 2.2). As a result, we obtained different weights and PSHI. Nevertheless, the pattern of the PSHI is similar. The statistical analysis in this verification also proved that the discontinuous permafrost region is more at risk from permafrost settlement than the continuous permafrost region. This indicates that a slight change in the importance of each pair (see Table 2.4) within the same importance rank of variables (see Table 2.2) does not affect the direction of PSHI.

For further discussion, we also created future PSHI. It was created with same variables and the same method that we took to create the current PSHI. However, we used temperature projections for the temperature data.

Larsen et al. (2008) assumed that each type of public infrastructure in Alaska has a different useful life period and hospitals and government buildings and like fixed assets have the longest "useful life" period - 40 years. For our model we adopted this "useful life" estimate and chose the year 2050, 40 years after 2010. Future temperature projections from the Scenarios Network for Alaska and Arctic Planning (SNAP) were used. By comparing surface temperature, precipitation, and sea level pressure between observation-based ECMWF 40 Year Re-analysis data (ERA-40) and global climate model (GCM) output variables, the five best performing GCM's across Alaska and the Arctic were determined to be: ECHAM5, GFLD21, MIROC, HAD and CCCMA (Walsh et al., 2008). The SNAP projection data was created by taking the mean values of output from these five GCM models. GCM output variables were downscaled via the delta method (Hayhoe, 2010, Hay et al., 2000) utilizing Parameter-Elevation Regressions on Independent Slopes Model (PRISM) from A1B IPCC scenarios, the mid range emission scenario.

In this model, the projected temperature in 2050 was treated as an independent variable assuming that other factors would remain the same. The SNAP data deals with uncertainty, by averaging across all five models. Nevertheless, SNAP data has many sources of inherent uncertainty such as simplified real world interaction, incomplete input data, and unpredictable variables (Scenarios Network for Alaska and Arctic Planning (SNAP), 2012).

Figure 2.8 shows the projected future changes in PSHI between 2010 and 2050, based on the SNAP projections described above. During this 40 year period, three types of changes are projected: PSHI increase (a positive value, red), no change (yellow), and PSHI decrease (negative value, blue). The darkest red color indicates a larger PSHI increase, whereas the darkest blue color represents a larger PSHI decrease. Our model indicates that the permafrost hazard risk will remain the same or slightly decrease in southern Alaska and decrease to a greater extent in southwest Alaska. We anticipated the great decrease in permafrost settlement hazard in southwest Alaska was the result of disappearing permafrost in this area in the future. There has been a PSHI decrease in the upper part of North Slope. According to the SNAP temperature projection which we used as a temperature variable, based on 2010 temperature, there has been a temperature decrease, and that seems to have caused the PSHI decrease in the area. Our model also indicates increase in northern Alaska, with the greatest increase expected in northwest Alaska (some parts of Northwest Arctic Borough). These results indicate that the risk of permafrost settlement will be most extreme in northwest Alaska.

This PSHI projection is the static permafrost settlement hazard model based on 2010 conditions, not a dynamic projection of permafrost settlement. In this model, because of limited data on these variables, we assumed that ecosystem conditions in 2010, such as snow cover, would remain the same. Although data availability and current information are crucial for analysis, Alaska's data-poor environment limited the scope of this research. For example, the inclusion of groundwater or drainage as variables in PSHI would strengthen the PSHI result. Furthermore, the vegetation map available was compiled in 1996, however, the pattern and distribution of vegetation may have changed because of external environmental changes such as wildfires, for example, the extreme fires at years of 2004 and 2005 in Interior Alaska, when 4.6 million ha were affected (Kasischke et al., 2012).

2.5.2. Maintenance Cost Analysis

The result of the maintenance cost analysis showed that areas with high PSHI have required greater maintenance costs than the areas with low PSHI. In addition, our maintenance cost analysis demonstrated that discontinuous permafrost regions have a higher PSHI value than continuous permafrost regions. Therefore, we can predict that discontinuous regions will require greater expenditures for infrastructure maintenance.

Figure 2.6 shows there are many roads located over regions with high PSHI values (> PSHI 3). For example, 67.6 % of the public roads are over in regions with over PSHI value 3. We already proved the hypothesis that the areas with high PSHI require greater maintenance cost in Section 2.3.3.2. Therefore, there is the possibility (and probability) that Alaska will have higher infrastructure maintenance costs in the future.

As stated above, data on Alaska and Alaskan infrastructure is limited. We only dealt with the maintenance costs of roads because of the paucity of cost data for other infrastructure. According to Larsen et al. (2008), Alaska has 19 different types (categories) of public infrastructure and, as of 2008, 16,000 separate infrastructure items. Therefore, inclusion of other types of infrastructure -such as airports, public buildings, and railroads together with actual cost data - will be needed for a comprehensive and thorough maintenance cost analysis.

We created a permafrost settlement hazard index related to temperature change and attempted to link the hazard index to infrastructure failure broadly. However, some researches insist that that numerous infrastructure failures in the Arctic region are not caused by permafrost warming, but by factors such as poor design, construction activity, the structure itself (radiation and snow accumulation) and poor maintenance (Shur and Goering, 2009, Instanes, 2003). Nevertheless, thawing of ice-rich permafrost has been identified as a primary problem for infrastructure and climate warming may accelerate ongoing permafrost degradation associated with construction activity and existing infrastructure (Instanes, 2003).

2.6. Conclusion

We created a permafrost settlement hazard index (PSHI) and investigated current permafrost settlement hazard in Alaska after examining ecosystem factors affecting permafrost settlement and calculating the weights for relevant factors and variables. A state-wide PSHI map was developed (Figure 2. 4). We devised a non-parametric statistical model which proved that Alaska's discontinuous permafrost region will be more at risk from permafrost settlement than its continuous permafrost region. In addition, the non-parametric statistical analysis of the relationship between PSHI and maintenance cost data revealed that the regions with high permafrost hazard value had higher road maintenance costs.

We also forecast future permafrost settlement risk in Alaska in 2050 using projected future temperature increases from published climate models. Our 2050 model indicates that the PSHI values in northwestern Alaska will be higher based on projected temperature changes and the risk of permafrost settlement will be more serious in the future. It also shows that current continuous permafrost regions will be at increased risk. This should be included in any future projection of economic damage.

Our study focused on Alaska. However, the PSHI model can be applied throughout the Arctic. Permafrost temperatures across the Arctic have increased during the past few decades and the depth of the active layer is also increasing in many regions (ACIA, 2004, Romanovsky and Osterkamp, 2001). Therefore, we can expect permafrost vulnerability in discontinuous permafrost areas. It is difficult to make direct conclusions from this research to infrastructure maintenance costs in other Arctic countries due to the varied nature of road density, construction, maintenance techniques, and other specific variables involved in maintenance costs. Also, maintenance costs may be affected by social factors such as economic stability and political issues. Nevertheless, as the climate changes, we can expect that risks of infrastructure failure by permafrost settlement related to climate warming may increase in many areas of the Arctic.

We focused on the permafrost settlement hazard to public roads of Alaska. However, other types of infrastructure including private infrastructure may also be impacted by permafrost thaw, requiring more frequent replacement and causing additional costs (Larsen et al., 2008). To cope with the permafrost settlement problems, it is necessary to anticipate and mitigate damages and economic loss. It is also important that decision-makers possess clear understanding of the damage size of climate warming on infrastructure.

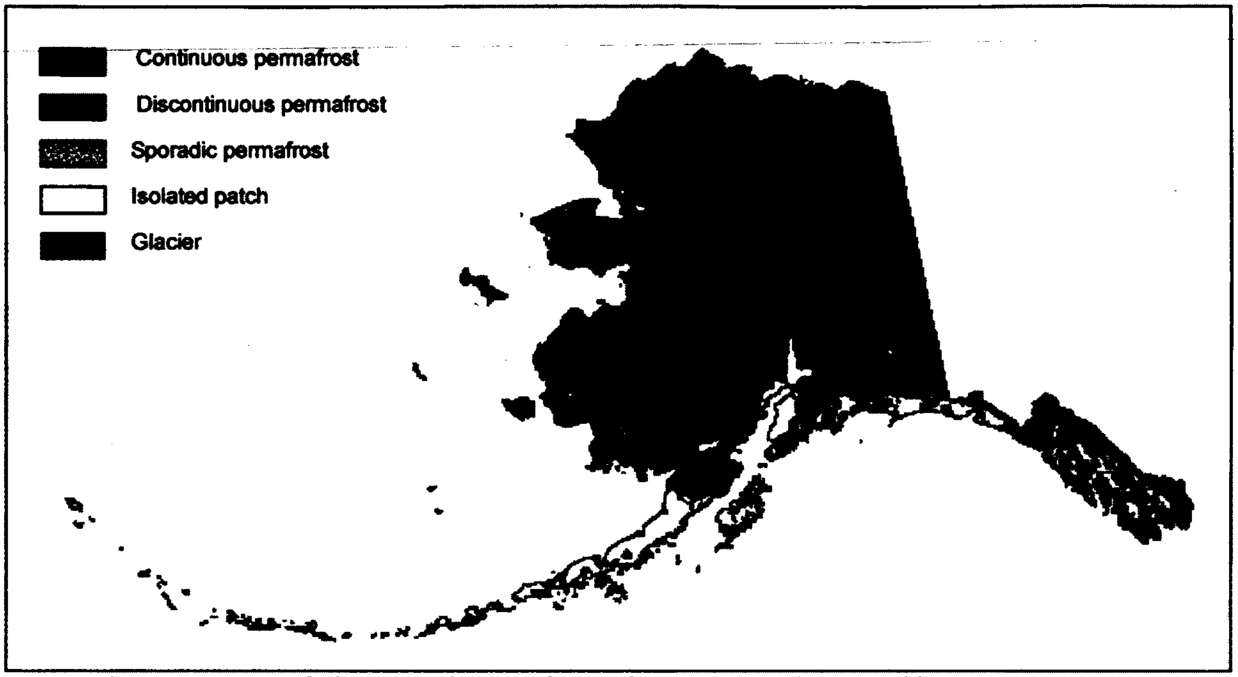

Figure 2.1 Extract of Circum-Arctic Map of Permafrost and Ground Ice Conditions (1998)
Source data:

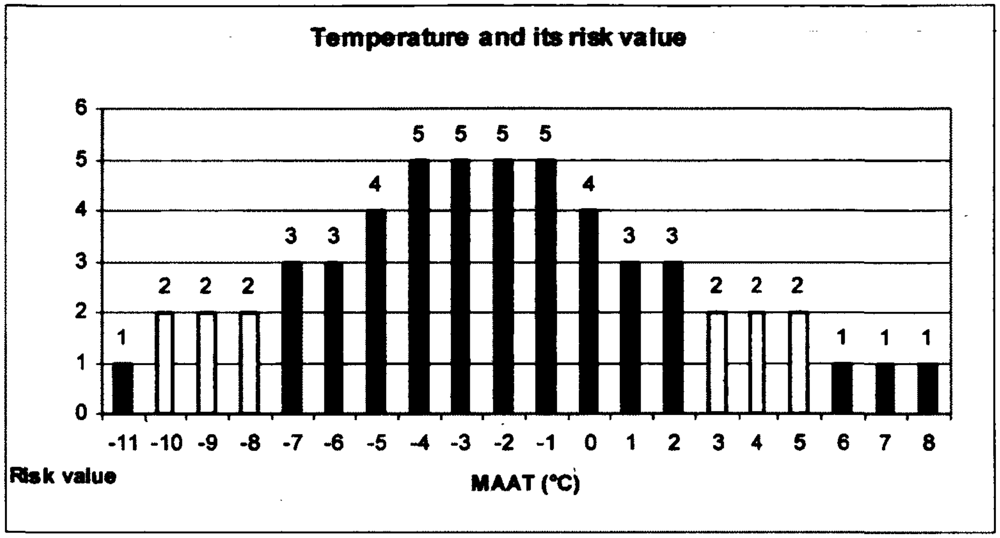

Figure 2.2 Temperature and its Risk Value.
The risk value for temperature was assigned according to the rounded off MAAT. Each color means a different risk value (Red:5, Blue:4, Green:3, Yellow:2, Orange:1).

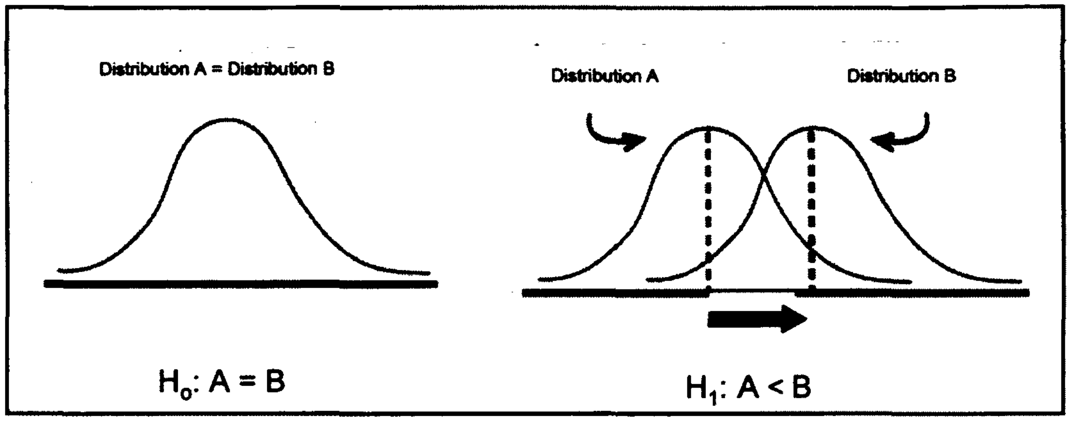

Figure 2.3 Null Hypothesis and Alternative Hypothesis

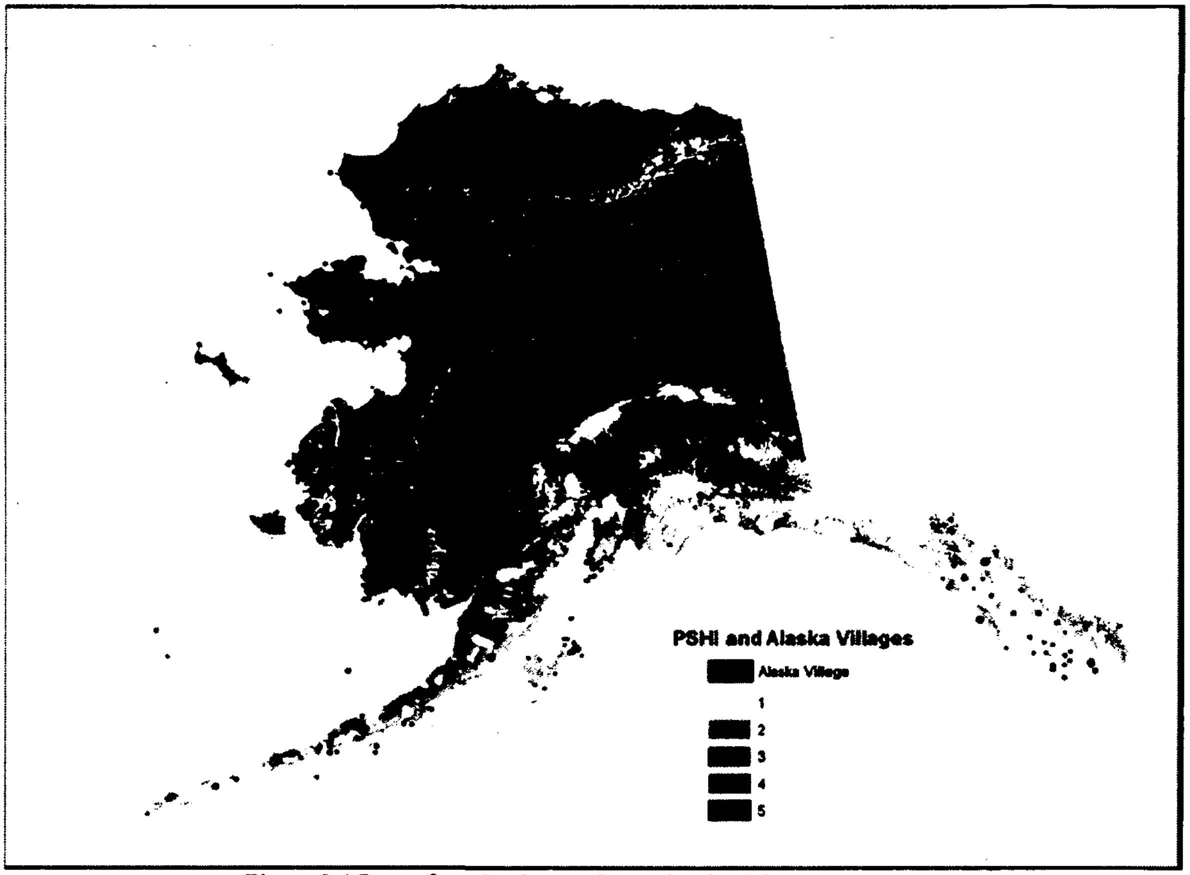

Figure 2.4 Permafrost Settlement Hazard Index Map

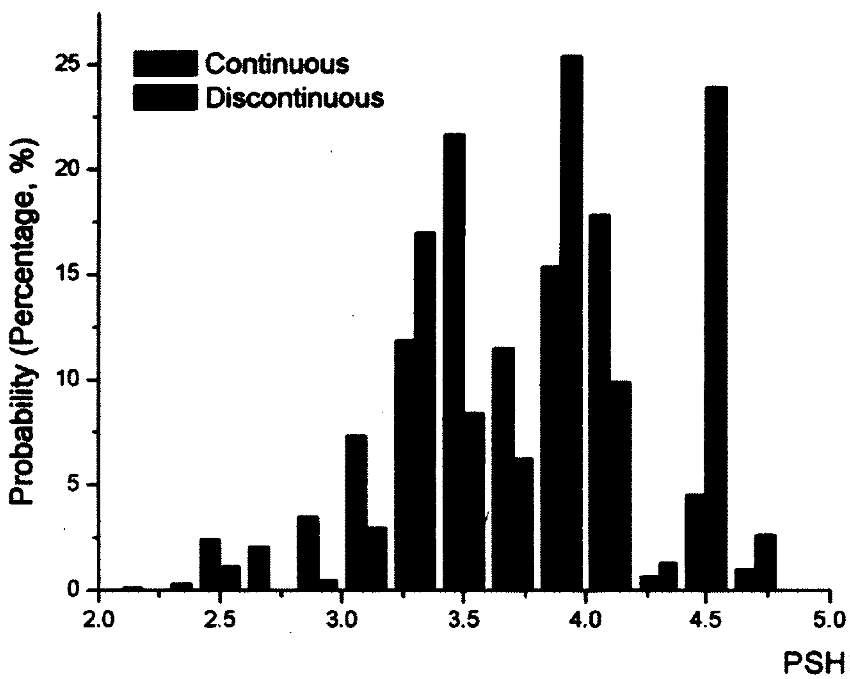

Figure 2.5 Probability of PSHI by Permafrost Regions

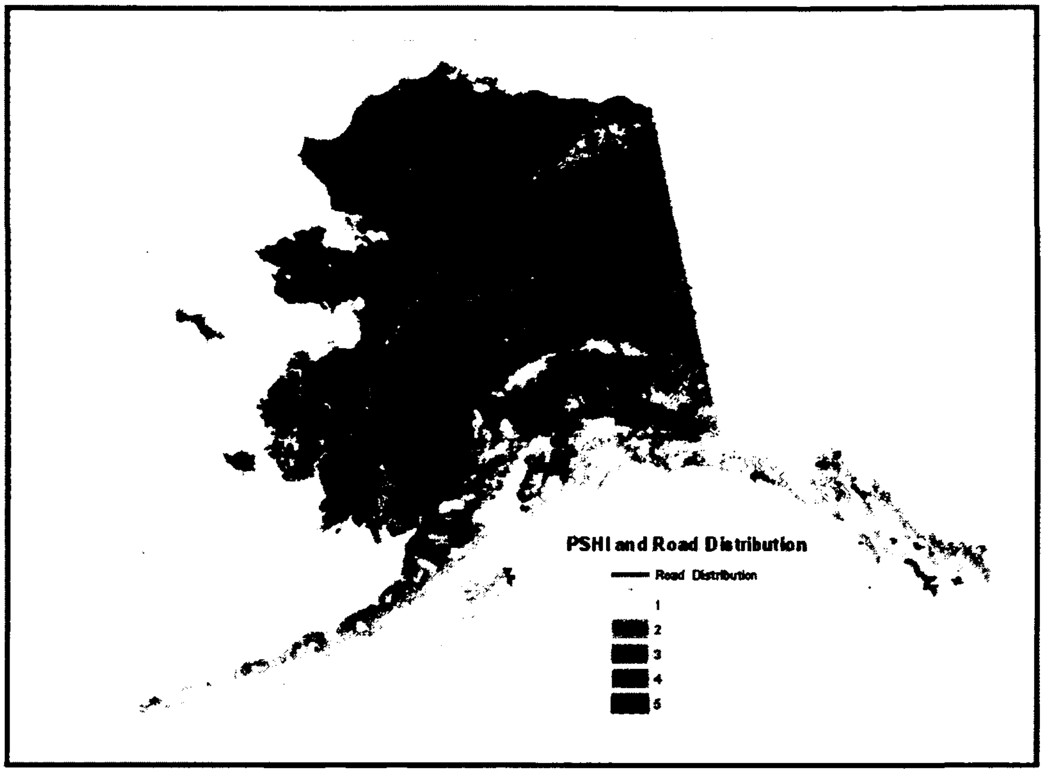

Figure 2.6 Permafrost Settlement Hazard Index Map and the Distribution of Alaska Roads

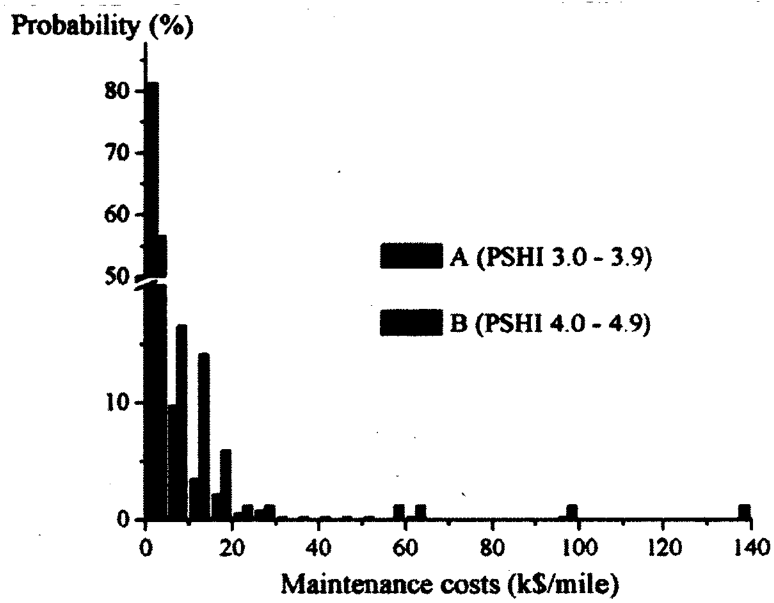

Figure 2.7 Probability of Maintenance Costs

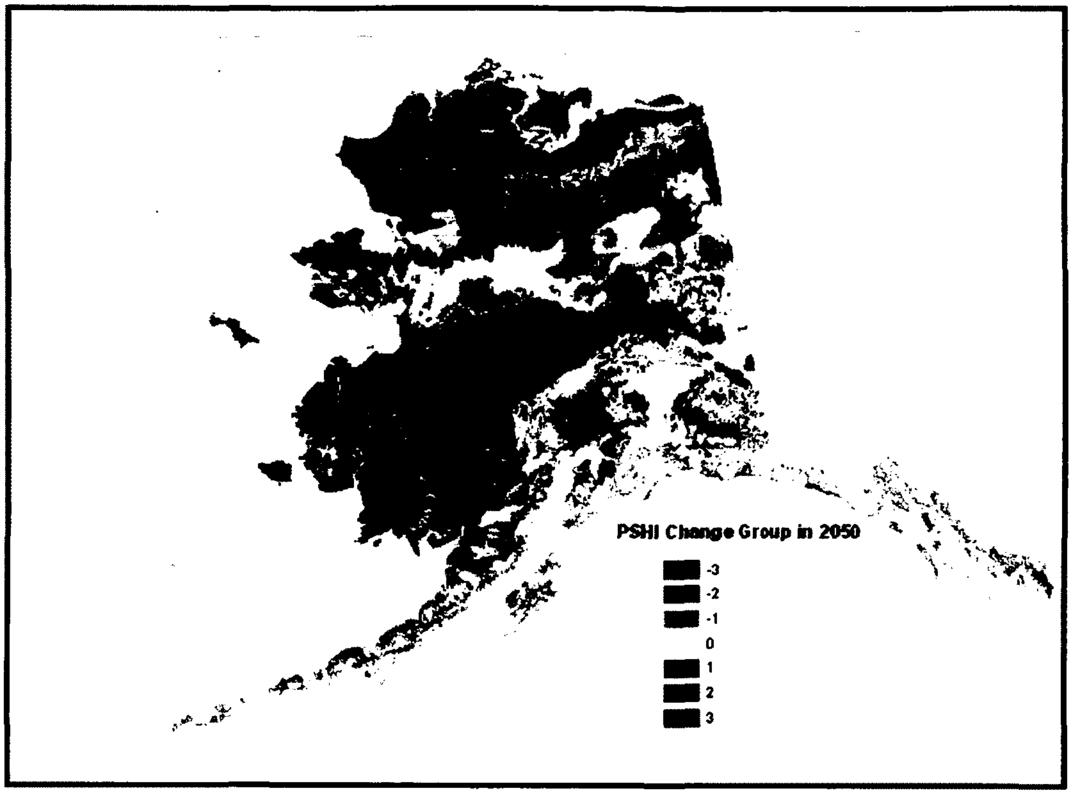

Figure 2.8 Permafrost Settlement Hazard Projected Change from 2010 to 2050

Table 2.1 Variables and their Map Sources for the PSHI

Variables	Data sources	Resolution
Ground ice content	(Jorgenson et al., 2008)	2km
Temperature	(Scenarios Network for Alaska and Arctic Planning (SNAP), 2010)	2km
Soil texture	(Jorgenson et al., 2008)	2km
Snow depth	(Jorgenson et al., 2008)	2km
Vegetation	(Fleming, 1996)	1km
Organic layer	(Jorgenson et al., 2008)	2km

Table 2.2 Importance Rank of Ecosystem Variables

Variable	Rank
Ground ice volume	1
Temperature	2
Soil texture	3
Snow depth	4
Vegetation	5
Organic Soil	6

Table 2.3 Scale of Relative Importance for Pairwise Comparison of Variables

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

* Intensities of 2, 4, 6 and 8 can be used to express intermediate value (Saaty, 2008).

Table 2.4 Judgments of Importance for AHP

Criteria/ Ecosystem Characteristics		More Important Characteristic	Relative Importance of Pair
A	B		
Ground ice volume	Temperature	A	3
Ground ice volume	Soil texture	A	5
Ground ice volume	Snow depth	A	7
Ground ice volume	Vegetation	A	8
Ground ice volume	Organic soil	A	9
Temperature	Soil texture	A	4
Temperature	Snow depth	A	5
Temperature	Vegetation	A	7
Temperature	Organic soil	A	9
Soil texture	Snow depth	A	3
Soil texture	Vegetation	A	5
Soil texture	Organic soil	A	7
Snow depth	Vegetation	A	3
Snow depth	Organic soil	A	5
Vegetation	Organic soil	A	3

Table 2.5 Variables Pairwise Comparison

	Ground ice Volume	Temperature	Soil texture	Snow cover	Vegetation	Organic soil
Ground ice Volume	1	3	5	7	8	9
Temperature	0.33	1	4	5	7	9
Soil texture	0.20	0.25	1	3	5	7
Snow cover	0.14	0.20	0.33	1	3	5
Vegetation	0.13	0.14	0.20	0.33	1	3
Organic soil	0.11	0.11	0.14	0.20	0.33	1

Table 2.6 Matrix of the Relative Importance and Inverses

$$A=\begin{bmatrix} 1 & 3 & 5 & 7 & 8 & 9 \\ 0.33 & 1 & 4 & 5 & 7 & 9 \\ 0.20 & 0.25 & 1 & 3 & 5 & 7 \\ 0.14 & 0.20 & 0.33 & 1 & 3 & 5 \\ 0.13 & 0.14 & 0.20 & 0.33 & 1 & 3 \\ 0.11 & 0.11 & 0.14 & 0.20 & 0.33 & 1 \end{bmatrix}$$

Table 2.7 Normalization of the Pairwise Weights

$$
\bar{A} = \begin{bmatrix}
0.52 & 0.64 & 0.47 & 0.42 & 0.33 & 0.26 \\
0.17 & 0.21 & 0.37 & 0.30 & 0.29 & 0.26 \\
0.10 & 0.05 & 0.09 & 0.18 & 0.21 & 0.21 \\
0.07 & 0.04 & 0.03 & 0.06 & 0.12 & 0.15 \\
0.07 & 0.03 & 0.02 & 0.02 & 0.04 & 0.09 \\
0.06 & 0.02 & 0.01 & 0.01 & 0.01 & 0.03
\end{bmatrix}
$$

Table 2.8 Variable Weights for the PSHI

Variable	Weight
Ground ice	0.44
Temperature	0.27
Soil texture	0.14
Snow depth	0.08
Vegetation	0.04
Organic soil	0.03

Table 2.9 Permafrost Settlement Related Road Maintenance Activities

Asphalt overlay pavement
Blading
Chip seal pavement repair
Crack sealing
Drainage structure maintenance
Drainage/ Erosion control
Dust control
Gravel surface repair
Hi-float pavement repair
Minor structural repairs
Pothole patching
Shoulder slope & ditch
Stabilizing

Table 2.10 Washington State Construction Cost Index

Year	2005	2006	2007	2008	2009	2010
CCI Index (1990=170)	176	228	230	241	223	232

Source : Washington State DOT (2011)

Table 2.11 Example of Averaged Maintenance cost/mile

Road name	Averaged PSHI	Miles	Averaged maintenance cost/mile (from 2005-2010)	Road category	Location	Permafrost region
Badger Road	3.99	11.174	979	Urban Collector	North Pole	Discontinuous
Auburn Drive	4.22	0.917	13855	Urban Collector	Fairbanks	Discontinuous
Ballaine Road	4.52	2.209	19913	Urban Collector	Fairbanks	Discontinuous

2.7. References Cited

ACIA (2004) Impacts of a warming Arctic: Arctic climate impact assessment, Cambridge University Press.

ACIA (2005) Arctic climate impact assessment, Cambridge University Press.

Alaska Climate Research Center (2012) Temperature Change in Alaska. In Alaska Climate Research Center (Ed.). Geophysical Institute, University of Alaska Fairbanks.

Alaska Department of Transportation and Public Facilities (AKDOT) (2010) Alaska road Maintenance cost from 2050-2010. Excel data, Personal contact from Ocie Adams, AK DOT&PF Commissioner's Office.

Andersland, O. B. & Ladanyi, B. (2004) Frozen ground engineering, Hoboken, N.J., John Wiley & Sons Inc.

Brown, J., O.J. Ferrians Jr., J.A. Heginbottom & E.S. Melnikov. (1998) revised February 2001.*Circum-Arctic map of permafrost and ground ice conditions*, Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. Digital Media. Available from ftp://sidads.colorado.edu/pub/DATASETS/fgdc/ggd320_map_alaska/

Brown, R. J. E., Pewe, T. L. & National Research Council Canada. Division of Building Research. (1973) Distribution of permafrost in North America and its relationship to the environment : a review, 1963-1973, Ottawa, National Research Council Canada.

Camill, P. (2005) Permafrost thaw accelerates in boreal peatlands during late-20th century climate warming. Climatic Change 68, 135-152.

Connor, B. & Charles, W. G. (1982) The compilation of highway and airport maintenance costs. Alaska Department of Transportation and Public Facilities. http://www.dot.state.ak.us/stwddes/research/assets/pdf/ak_rd_82_16.pdf.

Dey, P. (2003) Analytic hierarchy process analyzes risk of operating cross-country petroleum pipelines in India. Natural Hazards Review 4, 213-221.

Doré, G. (2005) Research on the performance of the Beaver Creek section of the Alaska highway. Department of Highways and Public Works, Government of Yukon.

Elliott, A. C. & Woodward, W. A. (2010) SAS essentials : a guide to mastering SAS for research, San Francisco, CA, Jossey-Bass.

Fleming, M. D. (1996) A statewide vegetation map of Alaska using a phenological classification of AVHRR data. Invited paper at Second Circumpolar Arctic Vegetation Mapping Workshop, Arendal, Norway, May 20-24, 1996. Arendal, Norway.

Galloway, D. L., Jones, D. R. & Ingebritsen, S. (1999) Land subsidence in the United States. US Geological Survey.

Goering, D. J. (1998) Experimental investigation of air convection embankments for permafrost-resistant roadway design. Seventh International Conference. Collection Nordicana, No 55, Whitehorse, Canada, p.319-326.

Gore, A. (Ed.) (1983) Mires: swamp, bog, fen and moor. Regional studies. Volume 4B, Elsevier, Amsterdam, The Netherlands.

Hay, L. E., Wilby, R. L. & Leavesley, G. H. (2000) A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. JAWRA Journal of the American Water Resources Association 36, 387-397.

Hayhoe, K. A. (2010) A standardized framework for evaluating the skill of regional climate downscaling techniques. Ph.D. thesis, University of Illinois, 153 p. https://www.ideals.illinois.edu/handle/2142/16044.

Instanes, A. (2003) Climate change and possible impact on Arctic infrastructure. Permafrost: Proceedings of the Eighth International Conference on Permafrost. A.A. Balkema.

Jorgenson, M. T., Racine, C. H., Walters, J. C. & Osterkamp, T. E. (2001) Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change 48, 551-579.

Jorgenson, M. T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E. A. G., Kanevskiy, M. & Marchenko, S. (2010) Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 40, 1219-1236.

Jorgenson, M. T., Yoshikawa, K., Kanveskiy, M., Shur, Y. L., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J. & Jones, B. H. (2008) Permafrost characteristics of Alaska. In Hinkel, D. L. K. A. K. M. (Ed.) In Proceedings ofthe Ninth International Conference on Permafrost, 29 June – 3 July 2008. Fairbanks, Alaska., Institute of Northern Engineering, University of Alaska Fairbanks.

Kääb, A. & Haeberli, W. (2001) Evolution of a High-Mountain Thermokarst Lake in the Swiss Alps. Arctic, Antarctic, and Alpine Research 33, 385-390.

Kasischke, E. S., Turetsky, M. R. & Kane, E. S. (2012) Effects of trees on the burning of organic layers on permafrost terrain. Forest Ecology and Management 267, 127-133.

Larsen, P. H., Goldsmith, S., Smith, O., Wilson, M. L., Strzepek, K., Chinowsky, P. & Saylor, B. (2008) Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environmental Change-Human and Policy Dimensions 18, 442-457.

Mclawhorn, N. (2006) Estimating construction costs and using construction cost indexes, Wisconsin Department of Transportation. http://on.dot.wi.gov/wisdotresearch/database/tsrs/tsrconstructioncostindex.pdf.

Myers-Smith, I. H., Harden, J. W., Wilmking, M., Fuller, C. C., McGuire, A. D. & Chapin, F. S. (2008) Wetland succession in a permafrost collapse: interactions between fire and thermokarst. Biogeosciences 5, 1273-1286.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2001) Subsidence risk from thawing permafrost - The threat to man-made structures across regions in the far north can be monitored. Nature 410, 889-890.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2002) Climate change and hazard zonation in the circum-Arctic permafrost regions. Natural Hazards 26, 203-225.

Osterkamp, T. (2005) The recent warming of permafrost in Alaska. Global and Planetary Change 49, 187-202.

Osterkamp, T. E. (2007) Characteristics of the recent warming of permafrost in Alaska. Journal of Geophysical Research-Earth Surface 112.

Osterkamp, T. E., Esch, D. C. & Romanovsky, V. E. (1998) Permafrost, In: G. Weller and P.A. Anderson (Eds.) Implications of Global Change for Alaska and the Bering Sea Region, Proceedings of a Workshop, University of Alaska Fairbanks, 3–6 June.

Osterkamp, T. E., Jorgenson, M. T., Schuur, E. A. G., Shur, Y. L., Kanevskiy, M. Z., Vogel, J. G. & Tumskoy, V. E. (2009) Physical and ecological changes associated with warming permafrost and thermokarst in interior Alaska. Permafrost and Periglacial Processes 20, 235-256.

Osterkamp, T. E. & Romanovsky, V. E. (1999) Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafrost and Periglacial Processes 10, 17-37.

Pappas, P. A. & DePuy, V. (2004) An overview of non-parametric tests in SAS: when, why, and how. *Proc. SouthEast SAS Users Group Conference* (SESUG 2004): paper TU04.

Pineda-Henson, R., Culaba, A. B. & Mendoza, G. A. (2002) Evaluating Environmental Performance of Pulp and Paper Manufacturing Using the Analytic Hierarchy Process and Life-Cycle Assessment. Journal of Industrial Ecology 6, 15-28.

Romanovsky, V. & Osterkamp, T. (2001) Permafrost: changes and impacts. In R. Paepe & V. Melnikov (Ed.) Permafrost response on economic development, environmental security and natural Resources. Dordrecht, Netherlands: Kluwer Academic Publishers, 297-315.

Romanovsky, V. E. & Osterkamp, T. E. (1995) Interannual variations of the thermal regime of the active layer and near-surface permafrost in northern Alaska. Permafrost and Periglacial Processes 6, 313-335.

Romanovsky, V. E. & Osterkamp, T. E. (2000) Effects of unfrozen water on heat and mass transport processes in the active layer and permafrost. Permafrost and Periglacial Processes 11, 219-239.

Saaty, T. L. (2008) Relative Measurement and Its Generalization in Decision Making Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors The Analytic Hierarchy/Network Process (To the Memory of my Beloved Friend Professor Sixto Rios Garcia). Revista De La Real Academia De Ciencias Exactas Fisicas Y Naturales Serie a-Matematicas 102, 251-318.

Scenarios Network for Alaska and Arctic Planning (SNAP) (2010) Historical temperature for 2009, Climate Research Unit (CRU) data downscaled to 2km, SNAP, University of Alaska. www.snap.uaf.edu. [Accessed Dec 2010].

Scenarios Network for Alaska and Arctic Planning (SNAP) (2012) Uncertainty. [online] Available from http://www.snap.uaf.edu/uncertainty.php [Accessed March 15, 2012].

Shaw, J., Taylor, R., Solomon, S., Christian, H. & Forbes, D. (1998) Potential impacts of global sea-level rise on Canadian coasts. Canadian Geographer/Le Géographe canadien 42, 365-379.

Shur, Y. & Goering, D. (2009) Climate change and foundations of buildings in permafrost regions. Permafrost Soils, 251-260.

Shur, Y. L. & Jorgenson, M. T. (2007) Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes 18, 7-19.

Smith, M. & Riseborough, D. (1996) Permafrost monitoring and detection of climate change. Permafrost and Periglacial Processes 7, 301-309.

Smith, M. W. & Riseborough, D. W. (2002) Climate and the limits of permafrost: A zonal analysis. Permafrost and Periglacial Processes 13, 1-15.

Smith, S. L., Burgess, M. & Geological Survey of Canada (2004) Sensitivity of permafrost to climate warming in Canada, Ontario, Geological Survey of Canada.

U.S. Arctic Research Commission Permafrost Task Force (2003) Climate change, permafrost, and impacts on civil infrastructure, Special Report 01-03, U.S. Arctic Research Commission, Arlington, Virginia.

Walsh, J. E., Chapman, W. L., Romanovsky, V., Christensen, J. H. & Stendel, M. (2008) Global climate model performance over Alaska and Greenland. Journal of Climate 21, 6156-6174.

Washburn, A. L. (1980) Geocryology : a survey of periglacial processes and environments, New York, Wiley.

Washington State DOT (2011) Trends in highway material costs, Washington State Department of Transportation. http://www.wsdot.wa.gov/biz/construction/CostIndex/pdf/constructioncosts.pdf.

Williams, P. J. (1995) Permafrost and climate-change - Geotechnical implications. Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences 352, 347-358.

Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. & Brown, J. (1999) Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. Polar Geography 23, 132-154.

Zhang, T., Osterkamp, T. E. & Stamnes, K. (1997) Effects of climate on the active layer and permafrost on the north slope of Alaska, USA. Permafrost and Periglacial Processes 8, 45-67.

Zhang, T. J. (2005) Influence of the seasonal snow cover on the ground thermal regime: An overview. Reviews of Geophysics 43, RG4002, doi:10.1029/2004RG000157.

Chapter 3 Estimating Damage Costs for Alaska Infrastructure at Risk from Climate Warming [1]

3.1. Abstract

Climate change may impact the Alaska infrastructure through permafrost thaw in the Arctic. Permafrost degradation affects the performance of infrastructure and increases maintenance costs. In this study, the damage cost to Alaska infrastructure caused by climate change from 2010 to 2050, is estimated using updated Alaska public infrastructure data and temperature projection data in Alaska.

We estimated the damage cost to public infrastructure in Alaska by estimating service life of the structures, computing the Life Cycle Cost, and finally calculating the Equivalent Uniform Annual Cost (EUAC) of all structures in an infrastructure database that was derived from the existing Alaska Public Infrastructure Database. Because of Alaska's unique geography and environment, we developed three model scenarios based on service life and modifying conditions to Alaska's infrastructure. The first, *Reference Service Life (RSL)*, shows infrastructure in standard normal conditions; the second, *Alaska Service Life Reduced (ASLR)*, takes into account the conditions present in Alaska which cause a structure's RSL to be modified and decreased; and, the third model, *Climate Change Service Life Reduced (CCSLR)*, illustrates the effect of permafrost settlement projected by temperature increases on the service life of infrastructure in Alaska.

The Factor Method was used to estimate the reduced service life of models ASLR and CCSLR by valuing the conditions (factors) which modify and affect the service life of infrastructure in Alaska. EUAC of each of the three models (RSL, ASLR, and CCSLR) was calculated and compared. Infrastructure damage cost was computed by calculating the difference between ASLR and CCSLR. In summary, damage cost was defined as the increased EUAC caused by the reduced service life of public infrastructure resulting from permafrost settlement attributable to temperature increases.

---

[1] Hong, E. & Trainor, S. Estimating damage costs for Alaska infrastructure at risk from climate change. Prepared for submission to Global Environmental Change.

By these calculations, the damage cost would be $106 million. This means that with the current climate change projection, climate warming may add about $106 million (7.5% of the ASLR EUAC) to the annual cost annually from 2010 to 2050 for public infrastructure. It also means permafrost settlements that are related to the climate warming will be the cause of the additional reduced service life of public infrastructure, hence increasing the cost of public infrastructure by $106 million annually. This $106 million means the relative size of damage cost to public infrastructure in Alaska when the impact of climate-induced permafrost settlement on public infrastructure was considered in estimating costs.

Abbreviations: Alaska Service Life Reduced (ASLR), Climate Change Service Life Reduced (CCSLR), Equivalent Uniform Annual Cost (EUAC), Factor Method (FM), Life Cycle Cost Analysis (LCCA), Reference Service Life (RSL)

3.2. Introduction

Abundant natural resources and improved mining and other extraction methods have accelerated economic development in the Arctic. Population growth, an increase in human settlements and urbanization and technological advances have resulted in a rapid expansion of physical infrastructure, such as transportation networks and communication lines (U.S. Arctic Research Commission Permafrost Task Force, 2003). Industries such as mining, fisheries, and tourism depend on the limited transportation infrastructure (National Research Council Committee on Climate Change and U.S. Transportation Research Board Division on Earth and Life Studies, 2008).

Average annual temperatures in Alaska have increased 1.7 °C since 1949 (Alaska Climate Research Center, 2012) and climate researches and models predict more serious and accelerated warming in northern latitudes (ACIA, 2004, Nelson et al., 2001, U.S. Arctic Research Commission Permafrost Task Force, 2003, Dey, 2003, Nelson et al., 2002, ACIA, 2005). Climate warming has caused much change in the Arctic and the U.S. Arctic Research Commission Permafrost Task Force (2003) has forecast permafrost thaw will continue to impact Alaskan infrastructure.

Osterkamp et al. (1998) have shown that thaw settlement is responsible for damage to infrastructure. Moreover, problems associated with permafrost thaw and its adverse effect on foundations and structures have been discussed in depth in specialist literature and research papers (U.S. Arctic Research Commission Permafrost Task Force, 2003, Romanovsky and Osterkamp, 2001, Nelson et al., 2001, ACIA, 2005). In addition, permafrost degradation affects the performance of infrastructure and increases maintenance costs (Fortier et al., 2011).

Some researchers point out that numerous infrastructure failures in the Arctic have not been caused by permafrost warming, but rather by poor design, construction activity, the structure itself (radiation and snow accumulation) and poor maintenance (Shur and Goering, 2009, Instanes, 2003). In addition, the disturbance of the road surface caused by construction activity often increases the mean annual surface temperature and subsequent permafrost degradation (Goering, 1998). Nevertheless, thawing of ice-rich permafrost has been identified as a primary problem for infrastructure; climate warming which causes additional permafrost thaw will only increase the problem (Osterkamp et al., 1998). However, there is minimal research on the economic costs of climate-induced permafrost thaw or estimates of infrastructure damage in the context of climate warming. Recognizing this, Larsen et al. (2008) conducted preliminary research which estimated the future costs to Alaska public infrastructure at risk from climate change. Nevertheless, the study was limited because of missing data, imprecision in data counting, and uncertain assumptions about thaw settlement of facilities built on permafrost. In our study, we updated the existing Alaska Public Infrastructure Database established by Larsen et al. (2008) including three additional infrastructure categories (post office, library, and the University of Alaska).

Every item (building, road, airport, bridge, etc.) in Alaska's physical infrastructure has an expected service life, the expected useful life for which is expected to be under in-use conditions when it is designed or constructed. In this study, we estimated the reduced service life of infrastructure and calculated the damage costs by estimating the reduced service life of infrastructure caused by climate-induced permafrost settlement. This study was designed to provide a methodology to estimate Alaska's infrastructure damage costs due to permafrost thaw caused by climate change.

3.3. Methodology

Larsen et al. (2008) built the Comprehensive Infrastructure Climate Lifecycle Estimator (ICICLE) at the University of Alaska's Institute of Social and Economic Research. They estimated the replacement costs and life spans for existing infrastructure in Alaska. Next, they calculated the annual net present value of infrastructure replacement over time for each structure under a base scenario and a climate change scenario and aggregated these values. Then, they computed the present value (PV) of these costs as the difference between the base case and the climate change case, concluding that climate change could add \$3.6–\$6.1 billion (or approximately 10%) in the twenty year period from 2010 to 2030 to future public infrastructure replacement costs in Alaska and \$5.6–\$7.6 billion in the 70 year period from 2010 to 2080.

Larsen et al. (2008) considered only infrastructure replacement costs from 2010 to 2050, whereas our study focuses on estimating the entire cost invested from construction to maintenance during the service life of the infrastructure using the Life Cycle Cost Analysis (LCCA). We expected comparing the entire cost of each case with and without impact of climate warming using LCCA will insure more accurate and comprehensive information on damage cost. An annual cost comparison among alternatives of different service lives is appropriate and the annual cost method is more accurately descried as Equivalent Uniform Annual Cost (EUAC) (Newnan et al., 2004). Therefore, an annual cost comparison among different service lives or even in a single service life under different conditions is valid and people would select the case whose annual cost is minimum (Newman, 2004). We estimated the damage cost calculating each EUAC of all structures in Alaska Public Infrastructure Database and aggregating them. EUAC can be expressed by the following formula:

Equation 1

$$EUAC = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

Where,

EUAC = Equivalent Uniform Annual Cost

P = the present value of all the costs

i = Discount rate (%)

n = Service life (years)

This can be implemented in MS Excel as:

EUAC = PMT(r,n,-P)

Where,

r = Discount rate (%)

n = Service life (years)

P = the present value of all the costs

To estimate EUAC, we need information about each infrastructure unit's Reference Service Life. ISO 15686-1 (2011) defines *Reference Service Life* as "service life of a product, component, assembly or system which is known to be expected under a particular set, i.e. a reference set, of in-use conditions and which can form the basis for estimating the service life under other in-use conditions."

When reference service life is modified by factors such as those described below (See 3.3.2) and when the modified service life is shorter than the reference service life, we call it *Reduced Service Life*. Figure 3.1 illustrates the differences in service life between Reference Service Life and Reduced Service Life. If we estimate the Reduced Service Life of each infrastructure unit, we obtain the EUAC difference between its Reference Service Life and Reduced Service Life. This EUAC difference ($EUAC_{\text{Reduced Service Life}} - EUAC_{\text{Reference Service Life}}$) is the increased annual cost from the annual cost of the Reference Service Life case. We estimated the Reduced Service Life using the Factor Method (FM), which was adopted by the International Organization for Standardization (ISO) in its Order 15686 as a comprehensive tool for service life prediction (ISO 15686-1, 2011).

Chapter 2 developed the Permafrost Settlement Hazard Index (PSHI) that analyzed the ecological characteristics regulating permafrost settlement for Alaska in 2010 and projected the PSHI to 2050 with temperature projection. Chapter 2 used the mean annual air temperature as an independent variable to project the future PSHI in Alaska. Using the Chapter 2's projected future PSHI, we estimated the Reduced Service Life of Alaskan infrastructure caused by permafrost settlement related to the climate warming. We considered the corresponding permafrost settlement hazard value as the condition of permafrost settlement for the area. We adopted the Chapter 2's projected 2050 PSHI for our estimated Factor E, Outdoor Environment, through 2050 (See Section 3.3.2).

In order to estimate the damage cost, we

(1) updated the Alaska Public Infrastructure Database established by Larsen et al. (2008);

(2) calculated the EUACs of each infrastructure type with *Reference Service Life (RSL)* information as a baseline;

(3) estimated the reduced service life considering all seven factors proposed by the FM. We assigned quantitative values for each factor considering Alaska conditions. Then we estimated the EUAC of this scenario, which we call *Alaska Service Life Reduced (ASLR)* EUAC;

(4) converted the PSHIs developed in Chapter 2 into factor values to estimate the reduced service life due to climate–induced permafrost settlement;

(5) estimated the reduced service life of infrastructure using the converted PSHI values to determine a *Climate Change Service Life Reduced (CCSLR)* model.

(6) estimated the *CCSLR* EUAC; and,

(7) obtained the EUAC difference between the CCSLR and the ASLR models.

We compared EUAC values directly for different service life (different models) when identical infrastructure (same costs, performance, etc.) is assumed for the shorter-life alternative at the end of its useful life.

In conclusion, we defined the damage cost as the increased EUAC caused by reduced service life of public infrastructure resulting from permafrost settlement attributable to temperature increases.

3.3.1 Updating Infrastructure Database and Estimating the EUACs

Data for the damage cost estimation is based on the Alaska Public Infrastructure Database which contains nearly 16,000 individual elements of public infrastructure and its location information in 19 categories, covering federal, state, and local government infrastructure units in Alaska (Larsen et al., 2008).

As a preliminary database for public infrastructure, this database has the following limitations. For example, there is the possibility of data omissions from each infrastructure category. Moreover, the Alaska Public Infrastructure Database did not include post offices, public libraries, and the University of Alaska, all of which are important types of public infrastructure in Alaska. The updated data set includes those three missing categories (post office, library, and the University of Alaska). Though private infrastructure, such as pipelines, underground cables, etc. is also affected by climate warming, there is great difficulty in collecting private sector data about infrastructure. Thus, because of this constraint, our study was limited to public infrastructure. Also, we excluded Alaska railroads and telephone lines in our updated Alaska Public

Infrastructure Database because of limited data on railroads and telephone lines cost components (e.g. construction cost, annual maintenance cost).

Our estimates of EUACs are based on the Life Cycle Cost Analysis method that estimates the entire cost of a structure over its expected service life. LCC (Analysis) is defined by the building and construction assets standard ISO15686 as "a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial costs and future operational costs (ISO 15686-2, 2001)." It considers not only investment cost, but also operating costs during the estimated life time (Gluch and Baumann, 2004).

However, because of the limited data on the cost of each component of each infrastructure type in Alaska, the LCC in this study was simplified as follows:

Equation 2

$$LCC = I - RES + OM\ \&\ R$$

LCC: Total life cycle cost in present value (PV) dollars

I: Initial cost

RES: Present value (PV) of residual value (resale value, salvage value)

OM&R: Present value (PV) of annual operating, maintenance, and repair costs

For infrastructure service life and cost components for LCCA, we relied on the cost data of Larsen et al. (2008) and Foster and Goldsmith (2008). We also used the RSMEAN, an online cost data and estimating tool for the three new infrastructure categories. We used actual expenditure data from the Community Capital Project Database (Alaska Department of Commerce Community and Economic Development, 2011) for the cost components of the three new infrastructure categories. We calculated the averages of the expenditure data by infrastructure type and used those averages throughout our study. To estimate and compare the EUACs, we needed the current age and the remaining service life of every infrastructure unit. For the cost analysis, we assumed that every infrastructure was built in 2010, and will be continuously in-use until the end of its service life. We focused on the difference of the EUACs of the same infrastructure's EUAC under different conditions, that is, the EUAC difference among the three models: RSL, ASLR, and the CCSLR.

Discount rates are needed to estimate the present values of costs, and result may be sensitive to the discount rate chosen. A higher discount rate means a lower present value of future cash flows (Tol, 2002). Discount rates used in LCCA for governments normally range from 3 to 5 percent, and represent the prevailing rate of interest on borrowed funds less inflation (Demo, 2006). We used a 3 % discount rate for our LCCA.

In addition, we assumed the size of the building infrastructure category to be of equal size by referring to the size guideline in the RSMEAN. Nevertheless, we assumed the larger sizes for the building category in the three largest cities in Alaska (Anchorage, Fairbanks, and Juneau) because of the cities' size and economic diversity.

Table 3. 1 below shows the 19 categories of infrastructure in the updated Alaska Public Infrastructure Database which contains 15,769 infrastructure units.

3.3.2 Service Life Prediction

Larsen et al. (2008) made the assumptions about thaw settlement of facilities on permafrost for each permafrost area, then, provided the information about reduction in service life for each climatic variable: 1) per degree increase in annual temperature, and 2) per inch increase in annual precipitation. The reduced service life of infrastructure because of climate change is critical because it determined directly the increased EUAC (the damage cost).

The ISO has published principles for assessing the service life planning of buildings and recognizes the Factor Method (FM) as a way of bringing together the consideration of each of the variables that is likely to affect the service life of a building. The FM was developed as a tool to support service life prediction in cases where there is a lack of adequate and reliable data (Abu-Tair et al., 2002). Therefore, instead of making assumptions about the CCSLR, we estimated the service life of the structures using the FM (ISO 15686-1, 2011). The FM is integral to determining the real service life of a structure and is based on a building's reference service life and the modifying factors that relate to the specific condition of the structure (Aarseth and Hovde, 1999, Silva et al., 2011). The FM brings both the materials of the building and its environment (inner and outer) into the estimation. It stresses that a structure's durability is a function of its components and the environments (El-Dash, 2011).

The FM considers seven factors and is formulated as follows:

Equation 2

$$ESL = RSL \times FactorA \times FactorB \times FactorC \times FactorD \times FactorE \times FactorF \times FactorG$$

Where,

ESL= Estimated Service Life

RSL= Reference Service Life

Factor A= quality of components

Factor B= design level

Factor C= work execution level

Factor D= indoor environment

Factor E= outdoor environment

Factor F= in-use conditions

Factor G= maintenance level

ISO 15686 proposes using three standard values for each factor: 0.8 - deteriorating effect; 1.0 - standard conditions; and 1.2 - favorable conditions (ISO 15686-1, 2000). Hovde (2005) provides the guidelines for the condition of factor values and its corresponding factor value (See Table 3.2). Factor values ranged from 0.2 to 5 dependent upon the condition of each factor.

Figure 3.2 shows the distribution of permafrost and location of infrastructure throughout Alaska. However, due to limited map availability in Alaska, positions of only five infrastructure types (airports, railroads, power lines, roads, and telephone lines) were shown. We overlaid the ice content map with the infrastructure maps using ArcGIS software (v.10). The GIS analysis revealed that a significant percentage of infrastructure is located on medium-high ice, specifically 71.8% in continuous permafrost regions, 30.9% in discontinuous permafrost regions, and 14.3% in sporadic regions. We used the aforementioned five infrastructure maps available to estimate the percentages of infrastructure on medium-high ice. If we had been able to locate maps for the other types of infrastructure, the percentages of infrastructure on medium-high ice would be different and more precise.

Where permafrost contains massive ground ice or is ice-rich, extensive thaw settlement may be expected (Romanovsky and Osterkamp, 2001, Smith et al., 2004, Doré, 2005). The thawing causes subsidence that creates depressions in the ground surface (Jorgenson et al., 2010, Romanovsky and Osterkamp, 2001) as well as stresses in structures on that ground. It follows that infrastructure located on ice-rich permafrost will be damaged as temperature increases (Larsen et al., 2008, Nelson et al., 2001, U.S. Arctic Research Commission Permafrost Task Force, 2003, ACIA, 2005). Although the FM considers seven factors, we assumed the other factors are not affected by warming and analyzed only one, the outdoor environment factor (Factor E) focusing on the effect of climate–induced permafrost settlement on service life.

Hovde (2005) defines Factor E (outdoor environment) as "a factor that expresses the outdoor environment exposing the actual component or structure." He also shows an example of guideline for selection of Factor E (also A) in relation to material qualities. According to his guideline for Factor E, in the case of a concrete structure, the Factor E value would decrease under freezing or thawing conditions.

Since we focused on Alaska, we assumed the thaw condition that is triggered by temperature warming is the most important factor in causing a decrease in service life. Chapter 2 developed the current PSHI for Alaska and projected PSHI to 2050 by examining the ecological characteristics which regulate permafrost settlement. Temperature was an independent variable in their study. They used temperature observation and projection data compiled by Scenarios Network for Alaska Planning (SNAP). The SNAP projection data was created by taking the mean values of outputs from the five Global Circulation Models which performed the best in Alaska: ECHAM5, GFLD21, MIROC, HAD and CCCMA (Walsh et al., 2008) from among the models that the Intergovernmental Panel on Climate Change (IPCC) presented (IPCC, 2007). These values are downscaled to 2km grid cells utilizing Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2012) from the A1B IPCC scenario, the midrange emission scenario (Scenarios Network for Alaska and Arctic Planning (SNAP). 2008). Figure 3.3 shows the current PSHI and projected PSHI in 2050 with location information of Alaska villages. The PSHIs in Chapter 2 range from one to five. An area with a lower PSHI has a lower risk of permafrost settlement, whereas the area with a higher PSHI has higher risk. Chapter 2, using actual cost data provided by Alaska Department of Transportation and Public Facilities (AK DOT & PF), shows that areas with higher PSHIs have paid more for the maintenance of the structures. Therefore, in this study, we assumed that there is a direct correlation between a relatively higher PSHI and more severe damage to infrastructure located in that higher PSHI area.

Since the corresponding permafrost settlement hazard value was considered as the condition of permafrost settlement for the area in this study, we converted the PSHI into Factor E.

By overlapping the PSHI map with the map of the Alaska villages, we were able to ascertain the PSHIs of each village. The original PSHI has a 2km x 2km resolution because of the 2km downscaled outputs of the SNAP projection data. Thus, first, we simplified the PSHI. By averaging several PSHIs within a village, each of the 355 Alaskan villages had only one PSHI. Then, we grouped the averaged PSHIs by intervals of 0.5. In the case of low PSHI values, we categorized them with at 1.0 interval because we assumed that the effect of a low PSHI value is not significant. Then, we could provide the corresponding factor value E of each interval, along with a description of each group. Table 3. 3 shows the conversion of proven PSHI to factor values for Factor E (Outdoor Environment). The descriptions for each value were adopted from the Guideline for Selection of Factor Values (Table 3. 2) and the ISO 15686's three standard values (0.8 for deteriorating effect; 1.0 for standard conditions; and 1.2 for favorable conditions (ISO 15686-1, 2000)). As an example, a factor value of 0.85 was applied to a structure subject to thaw conditions while factor value of 0.33 was applied to a structure in severe thaw conditions.

In another study dealing with the service life of public building in areas of harsh weather (Kuwait's coastal regions), El-Dash (2011) estimates the service life using the FM. However, instead of using a "deterministic" value for each factor, he uses qualitative values (low, most-likely, and high) based on discussions with Kuwaiti government engineers. He presents each corresponding factor value of each qualitative value.

Since we had no detailed and deterministic information for the other factors by each infrastructure unit due to data unavailability in Alaska, we also used qualitative values of low, most-likely, and high, for the modification factors and assigned corresponding quantitative values as El-Dash (2011) did. Table 3.4 indicates the qualitative description and classification of each of the seven factors in Alaska which we assigned to estimate the Alaska Service Life Reduced (ASLR). Values for each factor ranged from 0.85 and 1.2. It should be noted that since we had limited information about each factor, we valued the factors close to the reference service life (RSL) value of one (1).

For this study, it was necessary that each unit of infrastructure has an RSL. We used the service life estimates of Larsen et al. (2008), shown in Table 3.1, as substitute RSLs.

Next, we estimated the mean value of each of the factors (A-G) and estimated ASLR. Since we did not assign the each factor differently by location for the ASLR case, every infrastructure unit in the same category has the identical reduced service life (ie. All hospitals in Alaska, regardless of their location, would have the same reduced service life). This is another reason why we used the mean value of three qualitative values. The equation below provided by Moser (2004) was used to predict the mean value of each factor based on the assigned three qualitative values in Table 3.4 (Moser, 2004).

Equation 3

$$Mean = \frac{(Low + 2.95 Most\ \ likely + High)}{4.95}$$

Therefore, the mean EUAC of the ASLR model by infrastructure type was calculated using the Estimated Service Life (ESL), and the mean values of each of the seven factors (A-G). We estimated the CCSLR separately with a focus on the effect of climate–induced permafrost settlement (See Table 3.5). As in the ASLR model, we predicted the mean value of each factor based on the qualitative valuation of factors. For the service life of the CCSLR model, we kept the other six factors constant, except for Factor E, which was provided according to corresponding PSHIs in Table 3.3. This was done in order to compare the difference in reduced service life between the ASLR model and the CCSLR model. The value of Factor E (Outdoor Environment) in each category of infrastructure was assigned one of the six factor values which were based on the PSHI of each village (See Table 3.3).

Different from the ASLR model, the service life of each infrastructure unit of the CCSLR model is site dependent because Factor E (Outdoor Environment) is determined by the PSHI of each infrastructure's location.

3.4. Results

We estimated the RSL EUAC based on Life Cycle Cost Analysis. Table 3.6 indicates the RSL EUAC/unit and total RSL EUAC by infrastructure type. As shown in Table 3.6, the annual cost of constructing and maintaining the entire infrastructure in Alaska under the reference service life condition, is $1,420,157,000.

Table 3.7 shows the EUACs of the ASLR and CCSLR models. The total EUAC of the ASLR model is approximately $1,510,335,000. The EUAC of the CCSLR model was calculated by estimating a reduced service life adjusted to include the effects of permafrost settlement attributable to climate change. The total EUAC of the CCSLR model is $1,616,522,000.

Figure 3.4 graphically illustrates Table 3.7. The EUAC difference between the total RSL model and the ASLR model is approximately $90 million. The results suggest that the service life of infrastructure of in the ASLR model will be ended earlier than that in the RSL model because of the modifying factors not only Factor E but also other factors and this will add to annual cost. In addition, when we simply focus on the increased cost (EUAC) in the future, based on the RSL EUAC, the annually added cost for Alaskan roads will be $196 million. This means that an additional $196 million will be added annually to annual cost for public infrastructure from 2010 to 2050 due to the reduced service life under Alaska conditions including of the impact of climate –induced permafrost settlement.

When we subtracted the ASLR EUAC from the CCSLR EUAC, which we defined earlier as damage cost, damage cost would be $106 million. This means that $106 million will be added annually to annual cost due to due to additional reduced service life caused by climate change besides other factors, based on the calculated PSHI. This $106 million means the relative size of damage cost to public infrastructure in Alaska when the impact of climate induced permafrost settlement on public infrastructure was considered in estimating costs.

3.5. Discussion

3.5.1. Likely Share of Cost by Infrastructure Type

In this study, we concluded that given Alaska infrastructure's reduced service life and the current available temperature projections, the annual damage costs to Alaska infrastructure from 2010 to 2050 will be about $106 million. Figure 3.5 shows a breakdown of this $106 million damage cost by infrastructure types: airports account for 47%, roads - 14%, schools - 11% and miscellaneous government building (8%). These four infrastructure categories will make up approximately 80% of damage costs. It illustrates that the current locations of the infrastructure in those categories are sensitive to permafrost settlement causing the damage costs to increase. Looking at airports, there are many airports in mid and northern Alaska which are on discontinuous or continuous permafrost regions (See Figure 3.2). Their locations and proximity to areas of permafrost settlement are likely to make up the largest share of the projected 2010-2050 additional infrastructure damage costs. This seems unavoidable because public airports almost need to be located near population centers and villages for their convenient accessibility, regardless of permafrost region.

Figure 3.6 is a pie chart which shows the size of each infrastructure category in the total RSL EUAC (See Table 3.6). Four types of infrastructure, roads (24%), airports (25%), schools (19%), and miscellaneous government building (8%) make up 76% of the annual infrastructure costs. This explains infrastructure with a high total EUAC plays determining role in increasing damage costs. Alaska could either decrease or minimize the total damage cost in the future if Alaska avoids the current locations of the existing roads, airports, and schools, and move to lower permafrost settlement risk areas (villages) when Alaska has plans to rebuild and reconstruct them. In addition, to avoid, minimize and mitigate damage costs, this infrastructure (airports, roads, and schools) should be given a priority when relocating or rebuilding the most common public infrastructure. If there are no plans to rebuild or reconstruct the at-risk infrastructure or such change is not feasible, decision makers should adopt adaptative, environmental and sustainable methods, such as thermosyphon (Doré, 2005). In addition, investment in technology, innovation in construction methods and other environmental adaptation techniques should be given a priority.

3.5.2. Direction for Future Research

We determined the damage costs through the estimation of the reduced service life of infrastructure using the Factor Method. There are, however, criticisms of and limitations to the Factor Method (Silva et al., 2011). Much criticism has centered around the necessity of selecting a specific value for each factor. In addition, the multiplication of all factor values makes the estimated service life very sensitive to slight variations in each factor value (Hovde, 2005). The FM does not provide an exact service life; it provides only an estimated service life based on available information.

Nevertheless, the FM is used in service life planning and life cycle cost analysis because there is no other suitable methodology (Abu-Tair et al., 2002). The reliability of service life estimation depends on the quality of the data available and the appropriate assumptions (ISO 15686-1, 2011). Therefore, additional research is needed for reliable estimation of service life, especially as to reference service lives and the modifying factors reflecting different conditions.

3.5.3. Thawing Factors

We added the case of "Alaska Service Life Reduced (ASLR)" as a bridge case to differentiate the infrastructure damage related to climate warming from the infrastructure damage due to warming of permafrost by the structure itself and other factors. The cost increase caused by warming of permafrost by the structure itself and other factors, is accounted for in the ALSR case. Precisely, the EUAC of the ASLR model was estimated using the FM which considers seven factors: the effect of the quality of components, design level, work execution level, indoor environment, outdoor environment, in-use conditions and maintenance level. We demonstrated that the difference between the total RSL EUAC and ASLR EUAC is approximately $90 million. This leads one to believe that the service life of infrastructure will be terminated earlier because of those FM factors regardless of climate warming induced permafrost settlement, hence increasing its annual cost. This supports the fact that there have already been many infrastructure failures in Alaska and their maintenance costs irrespective of climate change, but relevant to other factors such as poor design, construction activity, structure itself (radiation and snow accumulation), and poor maintenance (Shur and Goering, 2009, Instanes, 2003) and some of which may cause permafrost settlement irrespective of climate warming.

Then, we accounted for the additional cost increase due to additional warming of permafrost caused by climate warming, in the CCSLR. First, we estimated the further reduction in service life from climate warming, which is CCSLR. Then, the damage cost was indicated by increase in EUAC from ASLR EUAC. The difference between the ASLR EUAC and CCSLR EUAC was $106 million. This demonstrated that about $106 million will be added to annual costs due to additional reduced service life caused by climate change besides other factors based on the ASLR case. This $106 million means the relative size of damage cost to public infrastructure in Alaska when the impact of climate induced permafrost settlement on public infrastructure was considered in estimating costs.

3.5.4. Comparison with the Preliminary Study

Larsen et al. (2008) did preliminary research, estimating the future costs for Alaska public infrastructure at risk from the climate change. They estimated the replacement costs with and without the effects of climate change and aggregated the present value of the annualized replacement costs of each case. In their model, when climate change is factored into the scenario, the structure loses useful life (equivalent to "service life" in our study) and this reduced useful life changes the present value replacement costs. They defined "future cost" as the difference in the annualized replacement costs between the base case and climate change case. By computing the difference in the aggregated present value (PV) of replacement costs between the base case and the climate change case, they concluded that projected climate change could add $3.6–$6.1 billion (10% to 20%) from 2010 to 2030 to future costs for public infrastructure in Alaska and $5.6–$7.6 billion (10% to 12%) from 2010 to 2080.

Nevertheless, as a preliminary study, their study was limited because of missing data, imprecision in data counting, and uncertain assumptions about thaw settlement of facilities built on permafrost. We developed the database and methodology moving beyond limitations of the preliminary study.

First, in our study, we updated the existing Alaska Public Infrastructure Database established by Larsen et al. (2008) including three additional infrastructure categories (post office, library, and the University of Alaska).

Secondly, we estimated the reduced service life of the structures caused by climate warming induced permafrost settlement. Larsen et al. (2008) set up assumptions about the thaw settlement of facilities on permafrost for each permafrost area, ultimately to draw the information of reduction in service life for two climatic variables (temperature and precipitation). We estimated the service life of the structures instead of providing assumptions to predict it. Nevertheless, we considered the temperature as the only factor which causes the service life of infrastructure to be reduced, because there is limited study of the effect of precipitation on permafrost settlement.

Thirdly, the biggest difference between their study and mine lies in the focused costs. The estimation in our study dealt with the whole cost required during the life cycle of the infrastructure, through the LCCA, while Larsen et al. (2008) considered only replacement costs. Also, instead of showing total cost from now to 2050, we presented the cost which would be required annually to build and maintain by the end of service life. Therefore, while Larsen et al. (2008) focused on the increased replacement costs assuming that there will be several life cycles through replacement activities depending on the affecting factors (temperature and precipitation), We compared the annual costs estimated with different service lives for only one life cycle of each case for the identical infrastructure (Thus, there is no replacement activity). We expected comparing the entire cost of each case with and without impact of climate warming using LCCA will insure more accurate and comprehensive information on damage cost of infrastructure. Nevertheless, uncertainty in LCCA lies in determining the service life of infrastructure and the chosen discount rate.

Finally, we tried to differentiate the infrastructure damage related to climate warming from the infrastructure damage due to warming of permafrost by the structure itself and other factors. We added the case of "Alaska Service Life Reduced (ASLR)" as a bridge case which connects the Reference Service Life (RSL) case (equivalent to "base case" in Larsen et al. (2008)'s study) and the Climate Change Service Life Reduced (CCSLR) case (equivalent to "climate change case" in Larsen et al. (2008)'s study). This case is added in order to account for the additional cost increase due to warming of permafrost caused by climate warming besides the cost increase due to warming of permafrost by the structure itself and other factors. We already defined the damage cost as "the increased EUAC caused by reduced service life of public infrastructure resulting from permafrost settlement attributable to temperature increases." Therefore, the baseline to estimate damage costs in our study is the EUAC of ASLR case while Larsen et al. (2008) estimated future cost based on "base case (equivalent to "RSL" in our study)."

When We simply focus on the increased cost (EUAC) in the future, based on the RSL EUAC (equivalent to "base case" in Larsen et al. (2008) study), the annually added cost for Alaskan public infrastructure will be $196 million. This means that there will be an increased annual cost of $196 million for public infrastructure from 2010 to 2050 due to the reduced service life under Alaska conditions including of the impact of climate –induced permafrost settlement. This $196 million is equivalent to 13.9% of the RSL EUAC. Larsen et al. (2008) concluded that projected climate change could add 10% to 20% of the base case from 2010 to 2030 and 10% to 12% from 2010 to 2080 to future costs for public infrastructure in Alaska. Interestingly, it seems that the increased percentage from the each baseline (base case in Larsen et al (2008) and the RSL EUAC in our study) is similar to each other although each estimate was calculated from different method and different focused cost.

3.6. Conclusion

Using updated data and methodology, we estimated the 2010 to 2050 damage cost caused by climate change to public infrastructure in Alaska. Estimated damage cost was determined by calculating the RSL, ASLR and the CCSLR EUACs and comparing them. In the CCSLR model, we determined the reduced service life caused by permafrost settlement resulting from climate warming. We then considered how the reduced service life caused by climate-induced permafrost settlement affected the annual costs of the public infrastructure.

First, we estimated the reduced service life using the Factor Method that considers seven factors which affect the service life of infrastructure in Alaska. Next, we estimated the reduced service life focusing on the effect of climate induced permafrost settlement in the future. Finally, we defined the damage cost as the increased EUAC caused by reduced service life of public infrastructure resulting from permafrost settlement attributable to temperature increases.

We conclude that approximately $106 million will be added annually to public infrastructure annual costs in Alaska from 2010 to 2050 because of climate change. In the estimated damage cost, we assumed that the service life of Alaska infrastructure will be further reduced because of the FM modifying conditions and future temperature projection.

Our findings indicate that Alaska should expect to pay a sizable additional sum of money (7.5% of the ASLR EUAC) necessary to keep and maintain the public infrastructure under changing climate and permafrost conditions. Therefore, managing and paying these damage costs to keep and maintain Alaska's physical inventory will be critical to the future of Alaska's economy (Cole et al., 1999).

Alaska will be able to decrease and minimize these estimated damage costs by relocating existing infrastructure to lower permafrost settlement risk sites. Nevertheless, most existing infrastructure is difficult to rebuild or relocate infrastructure. Therefore, an approach to decrease damage costs should be discussed from the planning phase of constructing infrastructure process. The PSHI map is expected to provide policy makers with information on lower risk area from permafrost settlement when villages have plans to rebuild or relocate at-risk infrastructure. In addition, the PSHI map shows that risks of permafrost settlement hazard are concentrated in discontinuous permafrost areas. Therefore, decreasing or mitigating damage costs in those areas should be a priority.

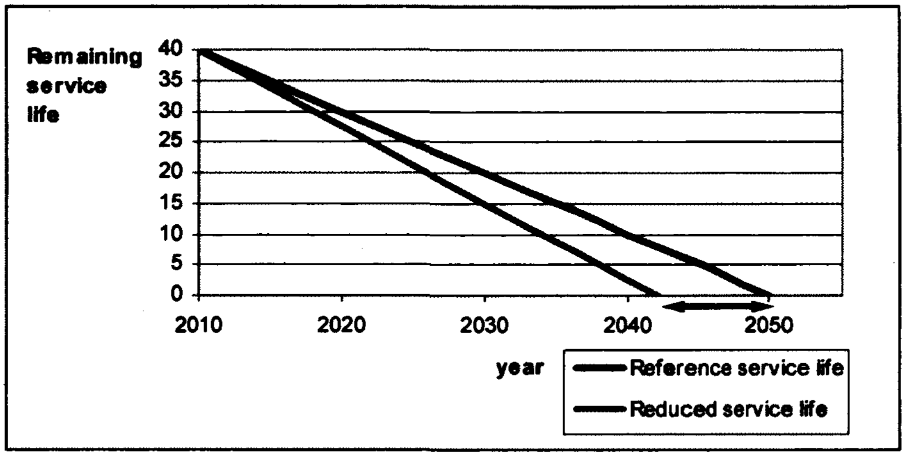

Figure 3.1 Comparison of Reference Service Life and Reduced Service Life

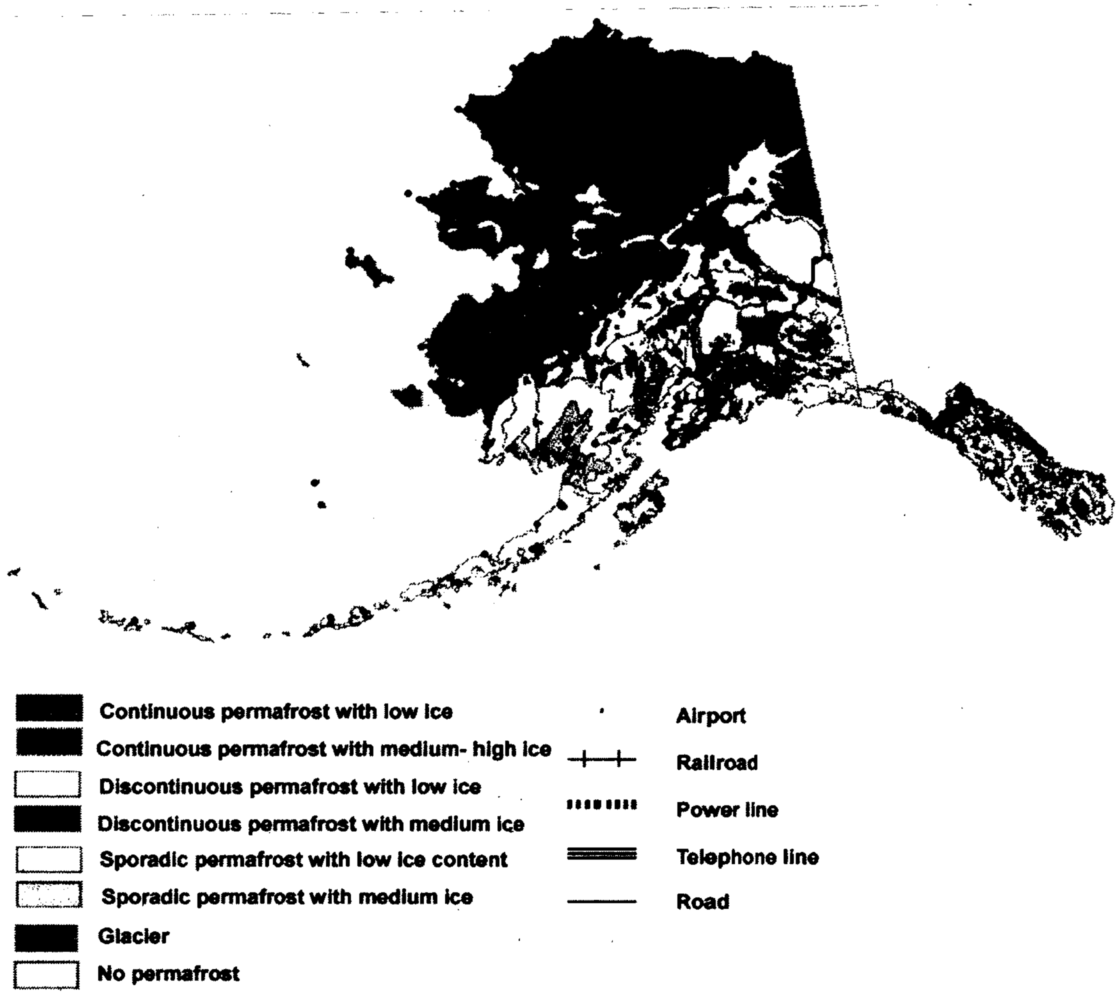

Figure 3.2 Distribution of Permafrost and Infrastructure in Alaska
Source: (Alaska State Geo-Spatial Data Clearinghouse, 2010, Brown et al., 1998)

Note : Relative abundance of ground ice in the upper 20 m is estimated in percent volume (>20%:, 10-20%, <10%, and 0%) (Brown et al. (1998)).

-High ice

: >20% for lowlands, highlands, and intra- and intermontane depressions characterized by thick overburden cover (>5-10m)

: >10% for mountains, highlands ridges, and plateaus characterized by thin overburden cover (>5-10m) and exposed bedrock

-Medium ice: 10-20%

-Low ice: 0-10%

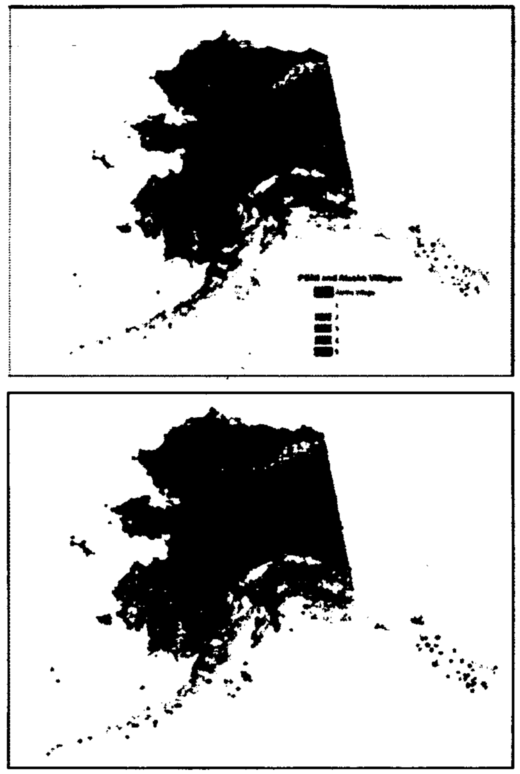

Figure 3.3A. Current PSHI (upper) and 3B. Projected PSHI (2050) in Alaska (bottom)

From Chapter 2. These maps show the PSHI together with locations of Alaskan villages. The PSHIs range from one (lower risk) to five (higher risk).

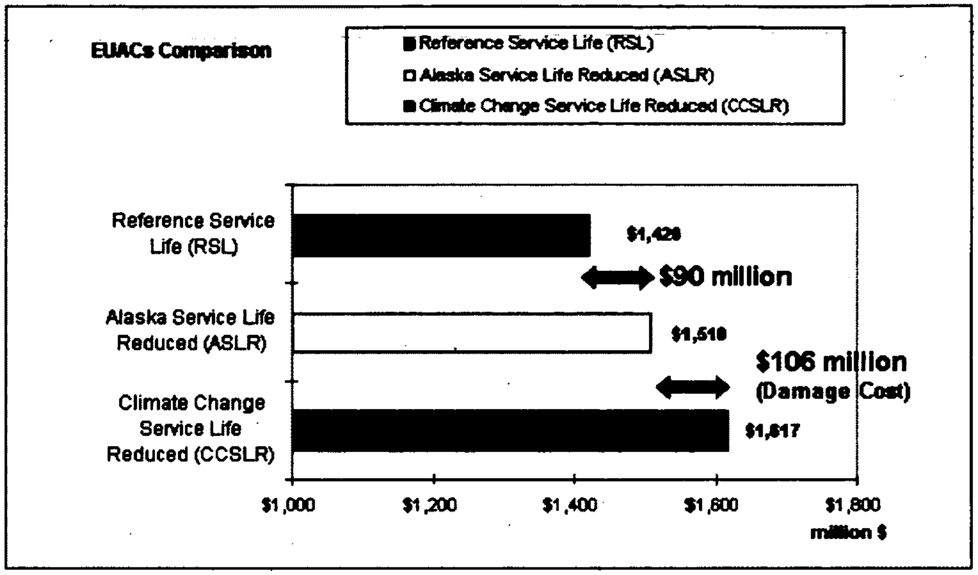

Figure 3.4 Comparison of EUAC by Service Life Models

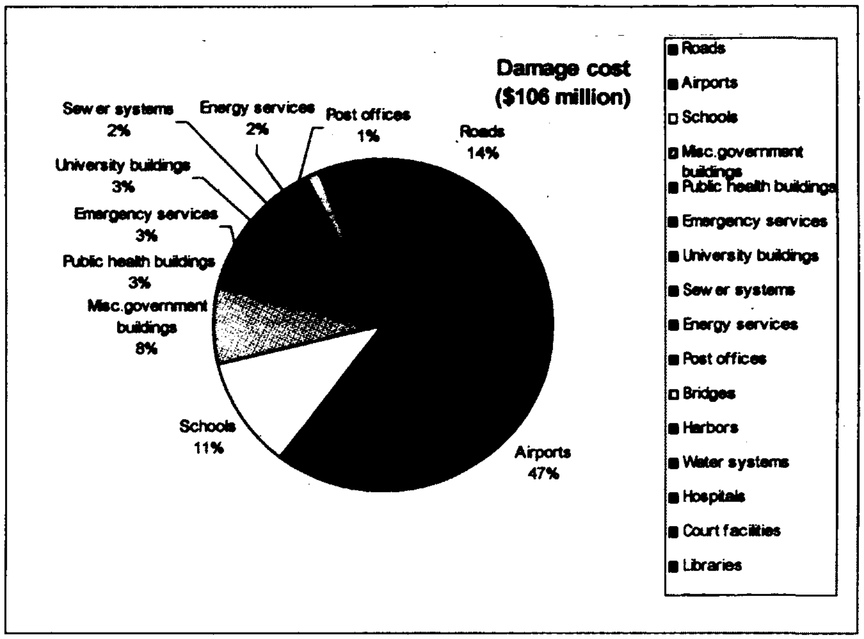

Figure 3.5 Likely Share of the Damage Cost by Infrastructure Type

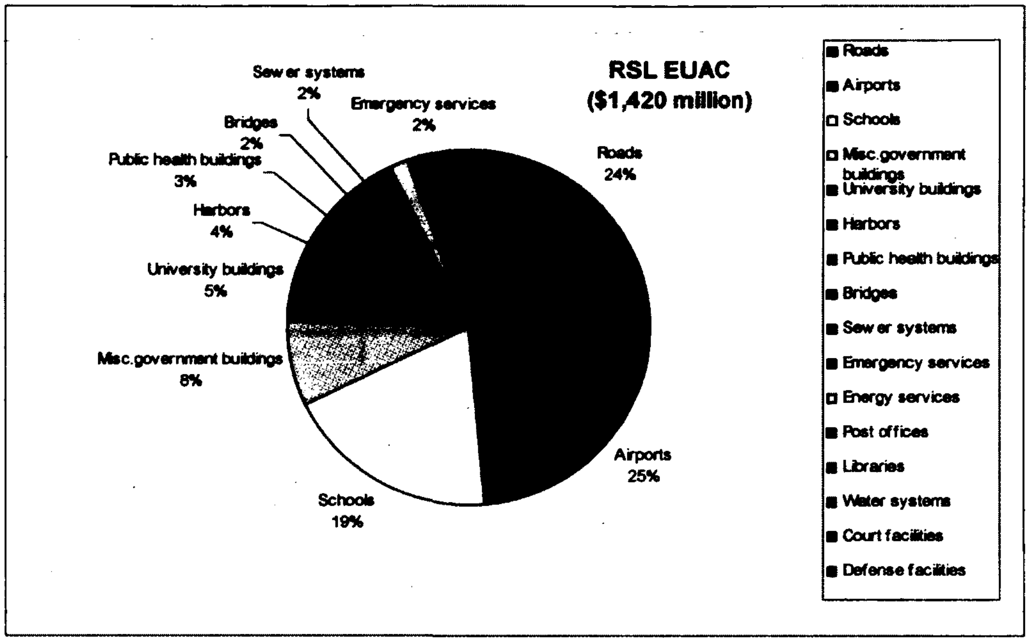

Figure 3.6 Likely Share of RSL EUAC by Infrastructure Type

Table 3.1 Updated Alaska Public Infrastructure Database

Type of infrastructure	Number	Service life (years)	Units	Infrastructure size[a] in three major cities Sq ft/ city count	Infrastructure size[a] Sq ft/ rural count
Airports	253	20	Whole		
Bridges	823 (31.4 mile)	40	Whole		
Court facilities	42	40	per sq ft	30000/6	15000/36
Defense facilities	178	40	per sq ft	6000/9	3000/169
Emergency services (fire station, other)	233	20	per sq ft	10000/10	5000/223
Energy services (fuel tanks, other structures off power grid)	302	30	Whole		
Harbors	131	30	Whole		
Hospitals	18	40	per sq ft	135000/3	6000/15
Law enforcement buildings (police station, prison, other)	66	30	per sq ft	11000/16	5500/50
Libraries	102	30	per sq ft	22000/7	11000/95
Misc. government . Buildings	1,571	30	per sq ft	7000/210	3500/1361
Post Offices	172	30	per sq ft	13000/15	6500/157
Power Plants	24	20	Whole		
Public Health buildings	346	30	per sq ft	7000/17	3500/329
Roads	10,476 roads (9564 miles)	20	per mile		
Schools	520	40	per sq ft	45000/117	22500/403
Sewer systems	124	20	Whole		
University buildings [b]	146	30	per sq ft	25000/146	-
Water systems	242	20	Whole		
Total	15,769				

Source: (Alaska Department of Commerce Community and Economic Development, 2011, Larsen et al., 2008, Foster and Goldsmith, 2008)

[a]: RSMEANS (http://www.reedconstructiondata.com/rsmeans/models/)

[b]: UAF facilities services

Table 3.2 Guidelines for Selection of Factor Values

Factor value	General conditions for selection of factor values						
	Factor A* : quality of components	Factor B : design level	Factor C* : work execution	Factor D : indoor environment	Factor E* : outdoor environment	Factor F : in-use conditions	Factor G* : maintenance level
5.0	Treated material				One relevant climate component is lacking		Maintenance with best available procedures
3.0	Excellent quality		Very good execution				
2.0	Very good quality				Mild climate		Very good maintenance
1.5	Good quality		Good execution level				
1.2							
1.0	To be applied if conditions are similar to the RSL conditions, or if a specific factor does not apply.						
0.85							
0.67	Reduced quality		Bad execution level				
0.5	Poor quality				Severe climate		Poor maintenance
0.33	Very poor quality		Wrong mounting and fixing				
0.2	Material not applicable				Extreme climate		Lack of maintenance

Source : Hovde (2005)

*: Hovde (2005) provided guidelines only for Factor A, C, E, and G.

Table 3.3 PSHI and Factor Value for Factor E

PSHI	Factor value	Description
1.0-2.0	1	Mild climate condition apply
2.0-3.0	0.9	Conditions are similar to the Reference Service Life (RSL) conditions
3.0-3.5	0.85	Thaw conditions may affect the service life
3.5-4.0	0.67	Thaw conditions apply
4.0-4.5	0.5	Serious thaw conditions apply
4.50-4.6	0.33	Severe thaw conditions apply

Table 3.4 Qualitative Description and Classification of Parameters for the ASLR Model

Factor	Description	Low	Most likely	High
A. Quality of components	Some buildings need rehabilitation	0.85	1	1.2
B. Design level	N/A	1	1	1
C. Work execution	No sign of distress due to execution defects	0.9	1	1.1
D. Indoor environment	No sign of indoor exposure	0.9	1	1.05
E. Outdoor environment	No expected damage from permafrost settlement	0.9	1	1.05
F. Usage condition	No expected change in usage	0.9	1	1.05
G. Maintenance	Below average commitment for maintenance is expected	0.8	0.9	1

Table 3.5 Qualitative Description and Classification of Parameters for the CCSLR Model

Factor	Alaska			
	Description	Low	Most likely	High
A. Quality of components	Some buildings need rehabilitation	0.85	1	1.2
B. Design level	N/A	1	1	1
C. Work execution	No sign of distress due to execution defects	0.9	1	1.1
D. Indoor environment	No sign of indoor exposure	0.9	1	1.05
E. Outdoor environment	Depends on the PSHI	Refer to Table 3		
F. Usage condition	No expected change in usage	0.9	1	1.05
G. Maintenance	Below average commitment for maintenance is expected	0.8	0.9	1

Table 3.6 Reference Service Life (RSL) EUAC

Infrastructure type	Number	Reference Service Life (years)	Unit	RSL EUAC (US$/unit)	Total RSL EUAC (US$)
Airports	253	20	whole	$1,407,113.24	$355,999,651
Bridges	823 (31.4 mile)	40	whole	$38,862.22	$31,983,609
Court facilities	42	40	per sq ft	$16.51	$11,887,899
Defense facilities	178	40	per sq ft	$16.51	$9,262,655
Emergency services (fire station, other)	233	20	per sq ft	$18.86	$22,915,404
Energy services (fuel tanks, other structures off power grid)	302	30	whole	$69,802.26	$21,080,284
Harbors	131	30	whole	$381,136.95	$49,928,940
Hospitals	18	40	per sq ft	$27.19	$3,548,481
Law enforcement buildings (police station, prison, other)	66	30	per sq ft	$18.71	$8,439,560
Libraries	102	30	per sq ft	$11.39	$13,659,688
Misc. government Buildings	1,571	30	per sq ft	$18.03	$112,270,105
Post Offices	172	30	per sq ft	$13.07	$15,891,143
Power Plants	24	20	Whole	$243,091.01	$5,834,184
Public Health buildings	346	30	per sq ft	$29.73	$37,774,998
Roads	10,476 roads (9,564 miles)	20	per mile	$34,988.68	$334,644,838
Schools	520	40	per sq ft	$18.91	$270,976,549
Sewer systems	124	20	Whole	$203,464.14	$25,229,553
University buildings	146	30	per sq ft	$21.04	$76,789,497
Water systems	242	20	Whole	$49,752.83	$12,040,184
Total	15,769				$1,420,157,222

Table 3.7 EUAC of Three Models

Infrastructure type	Service Life (years) Reference Service life (RSL)	Alaska Service Life Reduced (ASLR)	Total EUAC (US$) Reference Service life (RSL)	Alaska Service Life Reduced (ASLR)	Climate Change Service Life Reduced (CCSLR)
Airport	20	17.8	$355,999,651	$384,666,657	$439,721,639
Bridge	40	35.7	$31,983,609	$33,470,187	$34,439,664
Court facility	40	35.7	$11,887,899	$12,336,583	$13,203,631
Defense facility	40	35.7	$9,262,655	$9,612,255	$10,289,735
Emergency services (fire station, other)	20	17.8	$22,915,404	$24,323,731	$27,433,871
Energy (fuel tanks, other structures off power grid)	30	26.8	$21,080,284	$22,165,105	$24,336,329
Harbor	30	26.8	$49,928,940	$53,023,886	$55,943,321
Hospital	40	35.7	$3,548,481	$13,965,258	$14,856,220
Law enforcement (police station, prison, other)	30	26.8	$8,439,560	$8,873,872	$9,592,600
Library	30	26.8	$13,659,688	$14,362,635	$15,059,867
Misc. government . building	30	26.8	$112,270,105	$117,625,146	$126,950,454
Post office	30	26.8	$15,891,143	$16,708,924	$18,171,561
Power plant	20	17.8	$5,834,184	$6,192,739	$6,275,085
Public health	30	26.8	$37,774,998	$39,525,937	$43,040,715
Road	20	17.8	$334,644,838	$352,045,280	$365,997,056
School	40	35.7	$270,976,549	$281,135,062	$294,478,354
Sewer system	20	17.8	$25,229,553	$26,780,102	$29,367,117
University buildings	30	26.8	$76,789,497	$80,741,194	$87,387,955
Water system	20	17.8	$12,040,184	$12,780,145	$14,257,382
Total			$1,420,157,222	$1,510,334,697	$1,616,522,273

* The service life of the CCSLR model of each infrastructure unit depends on the location of infrastructure

3.7. References Cited

Aarseth, L. I. & Hovde, P. J. (1999) A stochastic approach to the factor method for estimating service life. In Lacasse, M. A. & Vanier, D. J. (Eds.) Proceedings of the 8th Durability of Building Materials and Components Conference. Vancouver, B.C., May 30 - June 3, pp. 1247-1256.

Abu-Tair, A. I., McParland, C., Lyness, J. F. & Nadjai, A. (2002) Predictive models of deterioration rates of concrete bridges using the factor method based on historic inspection data. 9th International Conference on Durability of Materials and Components. Rotterdam (Netherlands), in-house publishing.

ACIA (2004) Impacts of a warming Arctic: Arctic climate impact assessment, Cambridge University Press.

ACIA (2005) Arctic climate impact assessment, Cambridge University Press.

Alaska Climate Research Center (2012) Temperature Change in Alaska. In Alaska Climate Research Center (Ed.). Geophysical Institute, University of Alaska Fairbanks.

Alaska Department of Commerce Community and Economic Development (2011) DCED RAPIDS community capital project database.
http://www.commerce.state.ak.us/dca/commdb/CF_RAPIDS.htm. [Accessed June 2011].

Alaska State Geo-Spatial Data Clearinghouse (2010) Alaska infrastrucure maps, Digital Media, Available from http://www.asgdc.state.ak.us/.

Brown, J., O.J. Ferrians Jr., J.A. Heginbottom & E.S. Melnikov. (1998) revised February 2001.Circum-Arctic map of permafrost and ground ice conditions, Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. Digital Media. ftp://sidads.colorado.edu/pub/DATASETS/fgdc/ggd320_map_alaska/.
[Accessed June 2009].

Cole, H., Colonell, V. & Esch, D. (1999) The economic impact and consequences of global climate change on Alaska's infrastructure, Assessing the Consequences of Climate Change for Alaska and the Bering Sea Region, Edited by Gunter Weller, Patricia A. Anderson, Fairbanks, USA, p.43-57.

Demo, G. P. (2006) Life cycle cost analysis and discount rate on pavements for the Colorado Department of Transportation. Colorado Department of Transportation.

Department of Commerce Community and Economic Development (2011) DCED RAPIDS community capital project database, [online] Available from http://www.commerce.state.ak.us/dca/commdb/CF_RAPIDS.htm [Accessed June 15, 2011].

Dey, P. (2003) Analytic hierarchy process analyzes risk of operating cross-country petroleum pipelines in India. Natural Hazards Review 4, 213-221.

Doré, G. (2005) Research on the performance of the Beaver Creek section of the Alaska highway. Department of Highways and Public Works, Government of Yukon.

El-Dash, K. (2011) Service life prediction for buildings exposed to severe weather. Journal of Asian Architecture and Building Engineering 10, 211-215.

Fortier, R., LeBlanc, A.-M. & Yu, W. (2011) Impacts of permafrost degradation on a road embankment at Umiujaq in Nunavik (Quebec), Canada. Canadian Geotechnical Journal 48, 720-740.

Foster, M. & Goldsmith, S. (2008) Replacement cost for public infrastructure in Alaska: An Update, Institute of Social and Economic Research, [online] Available from http://www.iser.uaa.alaska.edu/Publications/webnote/Web_Note4a.pdf [Accessed June 15, 2011].

Gluch, P. & Baumann, H. (2004) The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Building and Environment 39, 571-580.

Goering, D. J. (1998) Experimental investigation of air convection embankments for permafrost-resistant roadway design. Seventh International Conference. Collection Nordicana, No 55, Whitehorse, Canada, p.319-326.

Hovde, P. (2005) The Factor Method–a simple tool to service life estimation. 10DBMC International Conférence On Durability of Building Materials and Components. Lyon, France, 17-20 April 2005.

Instanes, A. (2003) Climate change and possible impact on Arctic infrastructure. Permafrost: Proceedings of the Eighth International Conference on Permafrost. A.A. Balkema.

IPCC (2007) Climate change 2007 : the physical science basis : contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

ISO 15686-1 (2000) Buildings and constructed assets- Service life planning- Part 1: General principles International Standard Organization, Geneva.

ISO 15686-1 (2011) Buildings and constructed assets- Service life planning- Part 1: General principles and framework, International Standard Organisation, Geneva.

ISO 15686-2 (2001) Buildings and constructed assets- Service life planning - Part 2: Service life prediction procedures. ISO 15686-2:2001(E).

Jorgenson, M. T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E. A. G., Kanevskiy, M. & Marchenko, S. (2010) Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 40, 1219-1236.

Larsen, P. H., Goldsmith, S., Smith, O., Wilson, M. L., Strzepek, K., Chinowsky, P. & Saylor, B. (2008) Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environmental Change-Human and Policy Dimensions 18, 442-457.

Moser, K. (2004) Performance based methods for service life prediction: Part B - Engineering design methods for service life prediction. CIB report: Publication 294.

National Research Council Committee on Climate Change & U.S. Transportation Research Board Division on Earth and Life Studies (2008) Potential impacts of climate change on U.S. transportation, Washington, D.C., Transportation Research Board.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2001) Subsidence risk from thawing permafrost - The threat to man-made structures across regions in the far north can be monitored. Nature 410, 889-890.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2002) Climate change and hazard zonation in the circum-Arctic permafrost regions. Natural Hazards 26, 203-225.

Newman, D. (2004) Fundamentals of engineering: FE exam preparation, Kaplan Publishing.

Newnan, D., Eschenbach, T. & Lavelle, J. (2004) Engineering economic analysis, New York, Oxford University Press.

Osterkamp, T. E., Esch, D. C. & Romanovsky, V. E. (1998) Permafrost, In: G. Weller and P.A. Anderson (Eds.) Implications of Global Change for Alaska and the Bering Sea Region, Proceedings of a Workshop, University of Alaska Fairbanks, 3–6 June.

PRISM Climate Group (2012) Latest PRISM data. Oregon State University, [online] Available from http://prism.oregonstate.edu/ [Accessed March 15, 2012].

Romanovsky, V. & Osterkamp, T. (2001) Permafrost: changes and impacts. In R. Paepe & V. Melnikov (Ed.) Permafrost response on economic development, environmental security and natural Resources. Dordrecht, Netherlands: Kluwer Academic Publishers, 297-315.

Scenarios Network for Alaska and Arctic Planning (SNAP). (2008) Preliminary report to the Governor's sub-cabinet on climate change, SNAP. http://www.snap.uaf.edu/files/Draft%20Report%20to%20Governor's%20Subcabinet%209-08_0.pdf.

Shur, Y. & Goering, D. (2009) Climate change and foundations of buildings in permafrost regions. Permafrost Soils, 251-260.

Silva, A., de Brito, J. & Gaspar, P. L. (2011) Application of the factor method to maintenance decision support for stone cladding. Automation in Construction.

Smith, S. L., Burgess, M. & Geological Survey of Canada (2004) Sensitivity of permafrost to climate warming in Canada, Ontario, Geological Survey of Canada.

Tol, R. S. J. (2002) Estimates of the damage costs of climate change, Part II. Dynamic estimates. Environmental and Resource Economics 21, 135-160.

U.S. Arctic Research Commission Permafrost Task Force (2003) Climate change, permafrost, and impacts on civil infrastructure, Special Report 01-03, U.S. Arctic Research Commission, Arlington, Virginia.

Walsh, J. E., Chapman, W. L., Romanovsky, V., Christensen, J. H. & Stendel, M. (2008) Global climate model performance over Alaska and Greenland. Journal of Climate 21, 6156-6174.

Chapter 4 A study on the Cost-Effectiveness of Adaptation Methods for Alaska Roads to Climate Warming [1]

4.1. Abstract

Alternative construction methods have been used to withstand permafrost settlement for Alaska roads. Three of alternative construction methods (pre-thaw, thermosyphon, and Air-Cooled Embankments (ACE)) were chosen and reviewed as adaptation methods in order for Alaska roads in discontinuous permafrost region to withstand climate warming induced permafrost settlement. The three adaption methods were reviewed with a focus on cost effectiveness. We estimated that about $6 million will be added to annual costs of Alaska roads in discontinuous permafrost regions, due to additional permafrost settlement caused by climate change.

The most cost- effective adaptation method was identified by comparing the difference between the climate change case Equivalent Uniform Annual Cost (EUAC) and the adaptation case EUAC for each adaptation method. The pre-thaw method is considered to be the most cost effective method with the lowest EUAC. We also recommend ACE on a condition that coarse rocks are available to create a convection cell. Thermosyphon can still be used for potential severe permafrost degradation regions even though it does not have any price competitiveness.

Abbreviations: Air-Cooled Embankments (ACE), Alaska Service Life Reduced (ASLR), Climate Change Service Life Reduced (CCSLR), Equivalent Uniform Annual Cost (EUAC), Factor Method (FM), Life Cycle Cost Analysis (LCCA), Reference Service Life (RSL), International Organization for Standardization (ISO)

---

[1] Hong, E. & Trainor, S. A study on the Cost-Effectiveness of Adaptation Methods for Alaska Roads to Climate Warming. Prepared for submission to Global Environmental Change.

4.2. Introduction

Permafrost thaw and its adverse impacts on structures have been discussed in specialist literature (U.S. Arctic Research Commission Permafrost Task Force, 2003, Romanovsky and Osterkamp, 2001, Nelson et al., 2001, Saboundjian, 2008, Hoeve et al., 2006). Thawing permafrost causes settling and embankment instabilities, leading to a premature failure of existing structures (Saboundjian, 2008, Doré, 2005). Where permafrost contains ice-rich ground, extensive thaw settlement may occur (Romanovsky and Osterkamp, 2001, Smith et al., 2004, Doré, 2005). The thawing of ice-rich soils causes subsidence, creating depressions in the ground surface (Jorgenson et al., 2010, Romanovsky and Osterkamp, 2001) or stresses in the structures on that ground.

The average global surface temperature has increased since the mid-20th century (IPCC, 2007) and scientists and climate models project more accelerated changes in northern latitudes (U.S. Arctic Research Commission Permafrost Task Force, 2003, ACIA, 2004, Nelson et al., 2001, ACIA, 2005). Many impacts of the warming trend in the high northern latitudes are associated with permafrost (Nelson et al., 2002). Permafrost thaw and degradation in the Arctic caused by climate change has been anticipated to impact the Alaskan infrastructure (U.S. Arctic Research Commission Permafrost Task Force, 2003).

Nevertheless, there have been criticisms about the impact of permafrost warming on structure. Many infrastructure failures are relevant to other factors such as poor design, construction activity, structure itself (radiation and snow accumulation), and poor maintenance (Shur and Goering, 2009, Instanes, 2003). Disturbance of the road surface due to the construction also increases the mean annual surface temperature leading to permafrost degradation (Goering, 1998). Nevertheless, thawing of ice-rich permafrost has been identified as primary significant problem for infrastructure and climate warming trend will cause additional permafrost to thaw (Osterkamp et al., 1998). Therefore, we focused infrastructure damage caused by climate related permafrost thaw.

Numerous methods to counter the permafrost thawing effects have been used and tested by the Alaska Department of Transportation and Public Facilities (AK DOT&PF) since the 1960's (Doré, 2005). The AK DOT&PF has various repair options: to reconstruct a road completely, to perform remediation that may last for up to seven years, and to repair a road that may last up to 3 or 5 years (Cole et al., 1999).

Alternative construction methods associated with permafrost stability and their effectiveness have already been introduced in specialist literature (Saboundjian, 2008, Doré, 2005, Esch, 1982). There are two main design approaches for permafrost: passive and active. The passive method is to maintain the frozen state of soil, whereas the active method is to accommodate changes associated with the soil thawing under a given structure and modify foundation material conditions prior to construction (Shur and Goering, 2009). Usually, in the continuous permafrost zone, particularly in the permafrost areas with fine grained soils having high ice content, efforts are made to preserve frozen conditions. On the other hand, in the discontinuous zone, it may be necessary to remove frozen material that is susceptible to frost action (Seifert and University of Alaska Fairbanks Cooperative Extension Service, 2007), which is the active method.

Alternative construction methods in Alaska include pre-thawing, airduct, thermosyphons, Air-Cooled Embankments (ACE), geogrid reinforcement, berm, embankment thickening, embankment insulation, reflective surface, sunsheds, and snowsheds (Saboundjian, 2008, Doré, 2005). Some alternative construction methods can be used either in continuous permafrost or in discontinuous permafrost. However, most methods are usually used in discontinuous permafrost in order to prevent permafrost degradation and thaw settlement (Doré, 2005), because the temperatures of discontinuous permafrost are only a few degrees below the freezing point (Nelson et al., 2002, Jorgenson et al., 2001, ACIA, 2005). Therefore, the reaction in discontinuous permafrost to temperature increases can be more crucial. Alternative construction methods in discontinuous permafrost are the most important in order to avoid permafrost degradation problems (Doré, 2005).

Hoeve et al. (2006) describe the development of cost estimates to adapt the existing building foundations of infrastructure in Northwestern Canada to climate change impacts. Nevertheless, there are few studies of cost estimates of adaptation for existing infrastructure in Alaska. Climate change may eventually reduce the need for investment (e.g., reduced need for heating system in cold regions), however, an immediate impact of climate change could be an additional cost for the infrastructure to be adapted (Stephane, 2009).

We investigated costs for adaptation for the existing public infrastructure in Alaska. We defined the adaptation cost for infrastructure as the cost occurring additionally for the use of the alternative construction methods to withstand climate warming in the future. However, due to limited information on cost data in Alaska, we focused on public roads in Alaska. Alternative methods in discontinuous permafrost are the most important to avoid permafrost degradation problems (Doré, 2005). Therefore, we focused only on alternative methods for Alaska roads in discontinuous permafrost regions.

Doré (2005) classified adaptation methods into four categories: heat intake prevention, heat extraction from the embankment, reinforcement of the embankment and others. However, no cost data was available for methods such as embankment thickening, sunsheds, reflective surfaces and air ducts. The AK DOT&PF also compared the cost estimates in Alaska for selected adaptation methods (Alaska Department of Transportation and Public Facilities (AKDOT&PF), 1993). Nevertheless, since both AKDOT&PF (1993) and Doré (2005) have no full cost data for all adaptation methods, it was impossible to compare the cost effectiveness of all alternative construction methods explained so far. Thus, three of alternative construction methods (pre-thaw, thermosyphon, and Air-Cooled Embankments (ACE)) which have available cost data were chosen and reviewed as adaptation methods in order for Alaska roads in discontinuous permafrost region to cope with climate warming induced permafrost settlement. Then, we investigated the cost effectiveness of each method. We identified the most cost effective adaptation option by comparing the Equivalent Uniform Annual Cost (EUAC) of each adaptation method for identical roads. First of all, we estimated EUAC of current Alaska roads, then, we estimated EUACs of three adaptation cases: 1) Alaska roads constructed by Pre-thaw method, 2) Alaska roads constructed by ACE and 3) Alaska roads with thermosyphons.

Pre-thaw can be performed to attain thawing prior construction for unstable permafrost layers. However, it is recommended only for the shallow ice-rich permafrost layers (Esch, 1988). It is a permanent treatment that does not involve high construction costs and maintenance after construction (Doré, 2005). It is possible to increase the life of the embankment because settlements have occurred. Therefore, pre-thawing is a cost-effective method if time is available. Esch (1982) researched the cost-effectiveness of each pre-thaw mode as shown in Table 4.1. Asphalt placement represents the most expensive mode. The normal practice of road design in Alaska is the hand clearing mode, which is a simple removal of trees and brush where trees and brush are hand cut without disturbing the surface layer of mosses and grasses. The machine stripped mode is vegetation removal which results in accelerating thaw as a result of elimination of insulation of vegetation and exposure of the soil surface to direct incoming radiation (Esch, 1982). Table 4.1 shows that the change to machine stripping from hand clearing would result in cost saving. In addition, Table 4.1 shows the use of polyethylene film to increase soil temperature is the most cost effective (the cheapest) mode. However, polyethylene film is followed by additional works such as the placement of rocks, wood or soil as necessary to secure the film against wind. In addition, costs of the polyethelene film method depend on the thickness of the polyethelene film (Esch, 1982). As a result, our cost estimate for the pre-thaw method is based on the estimate for the machine stripped mode, which is the second cheapest pre-thaw mode, being followed by the modes of polyethelene film.

ACE is a method that is based on formation of convective cells using large poorly-graded porous rocks with a low fine content (Doré, 2005). ACE consists of an open rock matrix with a size range of roughly 6 to 12 inches that allows cold air during the winter to flow through and cool the ground. In the summertime, natural convection stops the flow of air, keeping cool air trapped within the rock matrix (Maynard, 2007, Goering, 2004). It can be incorporated in the center portion of the embankment beneath the asphalt or can be included on the embankment side slopes (Goering, 2004). The challenge with ACE is to find good coarse rocks that are big enough to allow the creation of convective cells. ACE has proven to be effective and is relatively inexpensive in areas where coarse rock is available. Otherwise, ACE is an alternative that can become costly. ACE method is also a technique that does not require maintenance after construction (Doré, 2005).

A two-phase closed *thermosyphon* is a heat transfer device used to transfer a large amount of heat at a high rate with a small temperature difference. This is achieved by evaporation of the working fluid in the evaporator section, condensing in the condenser section, and return of the condensate (Noie, 2005). The AK DOT& PF began a design for a new road building project near Fairbanks, Alaska, now known as Thompson Drive project. The mode of keeping the soils under Thompson Drive frozen incorporates hairpin thermosyphons. Thermosyphons are an excellent alternative, but are costly. Therefore, thermosyphons are typically used in severe permafrost degradation areas (Doré, 2005).

The cost for constructing each three option was considered as initial cost. These three cases were selected because of available cost data. The estimates of EUACs are based on the Life Cycle Cost Analysis (LCCA), a method used to estimate the entire cost of a structure over its expected life. We compared the annual cost of existing Alaska roads in discontinuous permafrost regions both with and without the adaptation cost of each adaptation option, under the current climate projection.

We addressed problems related to thawing permafrost for Alaska roads, estimated cost effectiveness of each adaption method to encounter the permafrost thawing, and then reviewed the possible technical and operational solutions. This research was ultimately designed to identify the cost-effectiveness of the adaptation methods for Alaska roads and to estimate the increased cost due to climate change, as well as the cost saved by the adaptation methods.

4.3. Methodology

The annual cost method is more accurately descried as EUAC and it can be used to compare infrastructure units with different service lives. When comparing the annual costs, people would choose the one whose annual cost is at the minimum regardless of the different service lives (Newman, 2004).

We calculated EUAC (EUAC) of each unit of infrastructure. This includes initial cost, residual value, and annual operation & maintenance (O&M) cost (See Equation 2). EUAC can be expressed by the following formula:

Equation 1

$$EUAC = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

Where,

EUAC = Equivalent Uniform Annual Cost

P = the present value of all the costs

i = Discount rate (%)

n = Service life (years)

This can be implemented in MS Excel as:

EUAC = PMT(r,n,-P)

Where,

r = Discount rate (%)

n = Service life (years)

P = the present value of all the costs

Reference Service Life is defined in International Organization for Standardization (ISO) 15686-1 (2011) as "service life of a product, component, assembly or system which is known to be expected under a particular set, i.e. a reference set, of in-use conditions and which can form the basis for estimating the service life under other in-use conditions." In this study, *Reduced Service Life* is defined as the modified service life which is shorter than the reference service life by factors (e.g., by Factor the Method described below) taking account of the specific in–use conditions (after Chapter 3).

Alternative construction methods to withstand permafrost settlement and degradation have already been introduced in specialist literature (Saboundjian, 2008, Doré, 2005, Esch, 1982). Therefore, we may guess that alternative construction methods (adaptation methods) would recover the reduced service life that was caused by permafrost settlement. We refer to this as *Prolonged Service Life*. Figure 4.1 shows the concept of reference service life, reduced service life and prolonged service life. Figure 4.1 was prepared to visualize three service lives (reference service life, reduced service life and prolonged service life). For example, a life of a road is shortened by 10 years from the original life of 40 years because of a permafrost settlement. Adaptation Methods would increase the shortened life of a road by 5 years. We call the shortened life, from 40 years to 30 years, a reduced service life and an extended life from a shortened life, from 30 years to 35 years, a prolonged service life.

Thus, we could identify the most cost- effective adaptation method by comparing EUACs calculated with estimated service life. We compared the EUAC difference between the climate change case EUAC and the adaptation case EUAC for each adaptation option. The climate change case means Alaska roads with "the reduced service life" resulting from climate-induced-permafrost settlement, which indicates a *Climate Change Service Life Reduced (CCSLR)* in Chapter 3. For the Alaska road estimation of the climate change case EUAC, we extracted the Alaska roads estimation from the Chapter 3's damage cost estimation.

Cost data for EUACs was based on Chapter 2 and Chapter 3's studies. Chapter 3 estimated the EUACs of 19 infrastructure types in Alaska with *Reference Service Life (RSL).* They estimated the reduced service life under Alaska conditions considering all seven factors proposed by the Factor Method (FM), which is adopted by the ISO in its 15,686 as a comprehensive tool for service life prediction (ISO 15686-1, 2011). They also estimated the EUAC of this case, which they call *Alaska Service Life Reduced (ASLR).*

Chapter 2 forecasted future Permafrost Settlement Hazard Index (PSHI) in Alaska in 2050 using Scenarios Network for Alaska and Arctic Planning (SNAP) temperature projections. Temperature projections are mean values of outputs from the five Global Circulation Models (GCM) (The GCM models performed the best in Alaska.: ECHAM5, GFLD21, MIROC, HAD and CCCMA (Walsh et al., 2008). These GCM values are downscaled to 2km grid cells along with the outputs from the A1B IPCC scenario, the midrange emission scenario (Scenarios Network for Alaska and Arctic Planning (SNAP), 2012). Chapter 3 converted the PSHI developed in Chapter 2 into factor values to estimate the reduced service life resulting from the permafrost settlement and estimated the reduced service life of each infrastructure, which is a *Climate Change Service Life Reduced (CCSLR)*. Then, they estimated EUACs of this case. Finally, Chapter 3 obtained the difference between the CCSLR case EUAC and the ASLR case EUAC and they defined the damage cost as "the increased EUAC caused by reduced service life of public infrastructure resulting from permafrost settlement attributable to temperature increases."

In order to compare costs of the adaptation options' case,

(1) We extracted the results of estimation data (for the cases of RSL, ASLR, and CCSLR) for roads which are located over the discontinuous permafrost area from Chapter 3;

(2) The EUAC was estimated for each three adaption options for an identical road;

(3) We compared EUACs obtained from (1) and (2) to identify damage costs for Alaska roads and how each adaptation option can decrease damage costs.

Our estimates of EUACs are based on the Life Cycle Cost Analysis. The ISO defines LCC (Analysis) as: "a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial costs and future operational costs (ISO 15686-2, 2001)." However, because of the limited data on the cost of each component of each infrastructure type in Alaska, the LCC in this study was simplified as follows:

Equation 2

Simplified $LCC = I + O\&M$

Where,

O&M: Present value (PV) of annual operation and maintenance costs

For the cost data, we used the cost information estimated by Esch (1982) for a pre-thaw method shown in Table 4.1. In terms of ACE and thermosyphon cost, we referred to costs estimated by Doré (2005) (See Table 4.2). The ACE and the pre-thaw cost data was presented for the case of Thompson Drive. However, we used these data throughout our study, due to the lack of reliable data. We referred to different sources for the cost information to estimate EUACs for adaptation methods, thus, they are based on different years. Therefore, the cost was normalized to 2010 US dollars by inflating the cost with 3% of inflation rate which is the same percentage that we used as a discount rate.

Discount factors are needed to estimate present values of costs, and discount rates used in LCCA normally range from 3 to 5 percent, representing the prevailing rate of interest on borrowed funds (Demo, 2006). We used 3 % of discount rate for our estimation. Also, since EUAC will be represented as $/mile, the reference price was also converted as $/mile.

Adaptation costs per mile were assumed with the following rationales:

* The road would be constructed in the discontinuous permafrost regions.

* The initial cost to construct roads in Alaska was taken as $303,220/mile, which represents the initial cost of road construction estimated in Chapter 3. LCC considered the cost to construct or build each adaptation method as an initial cost.

* We assume that every road was built in 2010 and will continuously be used until the end of its service life. We also assumed that the road would not be replaced, although the service life of the existing road is ended earlier than its RSL. This is because we compared the annual costs estimated with different service lives for only one life cycle of each case for the identical infrastructure (Thus, there is no replacement activity).

* We focus the difference in EUACs caused by permafrost settlement attributable to climate warming; we do not focus increased O&M as a result of climate warming. This is because that there is interchangeability between service life and maintenance costs. For example, if we don't spend anything on maintenance, the service life goes down and if we spend a lot on maintenance, the service life goes up. Thus, we assigned the same amount cost for the annual O&M for all three cases (RSL, ASLR, and CSLR).

* We assumed that adaptation methods would increase the reduced service life that was resulted from climate warming induced permafrost settlement. However, information on performance of each adaptation method was not sufficient to quantify the increased service life of

each adaptation function. Therefore, we equalized an increased service life on all adaptation methods; we assumed that the reduced service life of roads will be regained up to the service life of Alaska Service Life Reduced (ASLR).

* We had no information on an annual maintenance cost for each adaptation method, therefore, we rely on reasonable assumptions of annual maintenance costs based on the 'jury of executive opinion' approach, a common practice in some companies to ask opinions of key executives in establishing the forecast (Dessler et al., 2001). Since we assumed that permafrost thaw is preventable by adaptation methods, we also assume that the maintenance cost of each adaptation method will be lower than that of ASLR case. Discussion with engineers in the relevant agencies lead to the conclusion that pre-thaw, ACE, and thermosyphon will make the maintenance cost decrease as much as 20%, 30% and 40% of the ASLR maintenance cost, respectively.

* There was no information on service life for the adaptation methods. The assumptions on service life for the adaptation methods were also accomplished by the 'jury of executive opinion' approach. We concluded that the adaptation methods will work at least 20-25 years which is longer than the assumed road service life.

4.4. Results

The costs of road maintenance calculated in Chapter 3 are summarized in Table 4.3. They represented three EUACs of three different cases for the identical infrastructure: Reference Service Life (RSL) case EUAC, Alaska Service Life Reduced (ASLR) case EUAC and Climate Change Service Life Reduced (CCSLR) case EUAC. Table 4.3 and Figure 4.2 indicate the estimated EUACs for all Alaska roads of three cases from Chapter 3. They estimated EUACs of three different cases for the identical infrastructure assuming the same condition (construction cost, annual O&M cost) except for the service life. The difference between the total RSL EUAC and the ASLR is about $17.4 million. This means that , the service life of Alaska roads will be ended earlier than the expected reference service life and EUAC of the ASLR case will be higher than that of the RSL case. As such about $17.4 million will be added annually to annual costs for Alaska roads due to the estimated reduced service life. This $17.4 million means the relative size of additional cost to Alaska roads when the RSL is reduced due to affecting factors. When we subtracted the ASLR case EUAC from the CCSLR case EUAC, which Chapter 3 defined as a damage cost, damage cost for Alaska roads would be $14.0 million. This $14.0 million means the relative size of damage cost to Alaska roads when the impact of climate induced permafrost settlement on Alaska roads was considered in estimating costs. This indicates that there may be substantial additional costs ($14.0 million) for existing Alaska roads due to permafrost settlements that are related to the climate warming under the current climate projection.

Since we focus on adaptation methods in discontinuous permafrost areas (See Section 4.2), we sorted the data and estimation by permafrost regions. We sorted the database used for the Chapter 3's estimation and we determined that 2,565 miles are located over discontinuous permafrost regions. Figure 4.3 indicates the estimated EUACs for Alaska roads in discontinuous permafrost areas. This figure explains that about $5.9 million will be added annually to annual cost due to the estimated reduced service life caused by climate-induced permafrost settlement.

Table 4.4 indicates results of total EUACs and initial cost/mile and annual O&M/ mile of each case. The normalized initial costs in 2010 of thermosyphon, ACE, and pre-thaw were about $2.3 million, $414 thousands and $336 thousands, respectively. The annual O&M costs of thermosyphon, ACE, and pre-thaw were $8,765, $10,225 and $11,686, respectively. With the initial costs and the annual O&M cost and service life information, we estimated the EUAC/mile. As a result, the EUAC/mile of thermosyphon was the highest, which is $188,446/mile, followed by ACE ($42,137/mile) and pre-thaw ($37,592/mile). It seems that the higher EUAC/mile of all adaptation methods than the ASLR case is caused by high initial cost although the annual O&M for adaptation methods is smaller than that of the ASLR case.

Figure 4.4 shows the EUACs for thermosyphone, ACE, and pre-thaw along with three Alaska cases from Chapter 3. As mentioned earlier, the total EUAC difference between the ASLR case and the CCSLR case is about $6 million. This means that with the current temperature scenario, a climate warming could add about $6 million annually to annual cost for Alaska roads in discontinuous permafrost areas from 2010 to 2050. It also means that under the current temperature projection, there will be an additional annual cost of $6 million from 2010 to 2050, due to the reduced service life of the roads caused by permafrost settlements that related to climate warming. The EUAC of pre-thaw is about $96 million; $4 million lower than the CCSLR case, but $2 million higher than the ASLR case. This does not mean that Alaska can decrease the original damage cost of $6 million to $2 million annually with the pre-thaw option because this number is only an estimation, assuming that every road in discontinuous permafrost was built in 2010. This number is provided in order to address the economic benefit of adaptation options and to grasp the relative size of the economic benefit of adaptation options by comparing annual costs of Alaska roads in discontinuous permafrost regions with and without consideration of the benefit of the adaptation option under the current climate projection.

According to our calculation, the EUAC of ACE is about $108 million, which is 8 million higher than the CCSLR case. Nevertheless, we conclude that ACE is recommendable because the initial cost will decrease in areas where coarse rock is available (Doré, 2005). Therefore, the cost can be economically effective in these areas. In addition, since we had limited information, we simply assumed that the ACE will decrease 30% of the maintenance cost used for the normal road. This assumption could be high or low. In practice, the ACE method is also a technique that does not require maintenance after construction (Doré, 2005). Therefore, since there is not a large cost gap between ACE and CCSLR case, it is also possible that the ACE could become more cost effective if we collect more detailed data.

Nevertheless, the EUAC of thermosyphone is $483 million, which is much higher than the CCSLR case. These numbers illustrate, from the economic viewpoint, thermosyphon is not a good solution. However, since thermosyphon transfers a large amount of heat at a high rate with a small temperature difference, it is used in severe permafrost degradation areas (Doré, 2005). Our analysis is just simple cost comparison regardless of severity of permafrost degradation. Therefore, thermosyphon can still be used in regions where the potential severe permafrost degradation is expected.

4.5. Discussion

4.5.1. Thawing Factors

Although many studies address permafrost thaw that is associated with the climate change and its adverse impacts on structures (U.S. Arctic Research Commission Permafrost Task Force, 2003, Romanovsky and Osterkamp, 2001, Nelson et al., 2001, ACIA, 2005, Fortier et al., 2011), some studies explain that many infrastructure failures in the Arctic were caused by other factors such as poor design, construction activity, structure radiation and poor maintenance (Shur and Goering, 2009, Instanes, 2003). Disturbance of road surface during the construction activity may also increase road surface temperature leading to permafrost degradation (Goering, 1998).

Alternative construction methods have been used to withstand permafrost settlement for Alaska roads. Three of alternative construction methods (pre-thaw, thermosyphon, and Air-

Cooled Embankments (ACE)) were chosen and reviewed as adaptation methods in order for Alaska roads in discontinuous permafrost region to withstand climate warming induced permafrost settlement. We reviewed the three options with a focus on cost effectiveness. We found that under the current temperature projection, climate warming may add about $6 million to the annual costs annually from 2010 to 2050 for Alaska roads in discontinuous permafrost regions. The most cost- effective adaptation method was identified by comparing the EUAC of CCSLR which implies the impact of climate warming, with and without adaptation methods for one life time of each case. Therefore, we compared EUACs estimated with the different service life in order to understand the size of climate damage and the benefit of adaptation option. As a result, we concluded that pre-thaw method was the most cost effective method.

Alaska Service Life Reduced (ASLR) scenario was estimated by considering all factors proposed by the Factor Method, which affect the service life of infrastructure in Alaska. However, when we compared EUAC of adaptation options based on the ASLR EUAC, implication of the results are different. Based on the ASLR EUAC, the pre-thaw method is not cost effective. In addition, there is nothing that is economical based on the ASLR EUAC. Therefore, without consideration of climate induced permafrost, none of the adaptation options is recommended from cost effectiveness perspective. This indicates all adaptation options are still expensive although we considered the road failures relevant to other factors in Alaska such as poor design, construction activity, structure itself, and poor maintenance. Economic inefficiency of adaptation options supports the fact why these options have not been widely used in Alaska.

In order to estimate the EUAC of adaptation options, we assumed that the reduced service life of roads resulted from climate induced permafrost settlement will be regained up to the service life of Alaska Service Life Reduced (ASLR). As mentioned above, alternative construction methods have been implemented to withstand permafrost settlement irrespective of climate warming. However, we did not differentiate the EUAC of alternative construction method case which is in place to withstand permafrost settlement but which does not consider additional permafrost settlement caused by climate warming, because this estimation would need another assumption on the prolonged service life (e.g. the reduced service life of roads resulted from permafrost settlement will be regained up to the reference service life), and adding another assumption on the prolonged service life may compound the inherent uncertainty in the model. Nevertheless, this study could provide a better detailed implication on adaptation costs by differentiating the case of the EUAC of alternative construction option which are in place regardless of consideration of climate warming induced permafrost settlement.

Nevertheless, we focused adaptation to cope with climate induced permafrost settlement. Chapter 3 already insisted that the added problem of climate change induced permafrost settlement requires more costs to the annual costs. We estimated damage cost and adaptation cost with the Chapter 3's result that based on the A1B IPCC scenario, the midrange emission scenario (Scenarios Network for Alaska and Arctic Planning (SNAP), 2012). However, it is possible that the estimated damage cost may need to be increased due to the actual emissions trajectory, which is close to the highest-emission scenario (Raupach et al., 2007) and engineers must address permafrost settlement related to climate warming to preserve roads under projected future climate conditions. Therefore, cost comparison based on CCSLR will be an appropriate approach to address additional risk in permafrost settlement due to climate warming.

4.5.2. Limitation

Since Alaska has very limited cost data, we had to select some adaptation methods based on data availability. We also had to depend on assumptions in terms of the service life of the adaption methods and annual O&M cost for adaptation methods. In particular, we did not differentiate the increased service life by adaptation option; we assumed that the reduced service life of roads for all adaptation methods' cases will be regained up to the service life of Alaska Service Life Reduced (ASLR) case identically. However, this assumption may underestimate the function of adaptation methods. Also identical assumption on the performance of adaptation methods may also not be true. Therefore, for the better estimation, detailed information on the performance and cost of the adaptation methods will be necessary.

As mentioned above, we estimated damage cost and adaptation cost based on the A1B IPCC scenario, the midrange emission scenario (Scenarios Network for Alaska and Arctic Planning (SNAP), 2012). However, the actual emissions trajectory since 2000 was close to the highest-emission scenario, A1FI and the emissions growth rate since 2000 exceeded that for the A1FI scenario (Raupach et al., 2007). This also indicates our cost baseline (PSHI) may underestimate the impact of climate-induced permafrost settlement on infrastructure and this may also cause to underestimate the damage costs.

Therefore, activities for better estimation include: evaluation of the potential thaw settlement of each adaptation method, assessment of the performance of adaptation methods, cost estimation with different emission scenarios, and accumulation of cost used for construction and maintenance.

4.6. Conclusion

We reviewed three adaptation methods in order to recommend the most cost effective adaptation method for Alaska roads in the future. We estimated future adaptation costs for Alaska roads in discontinuous permafrost regions and investigated the cost effectiveness of each method. We identified the most cost- effective adaptation method by comparing the difference between the CCSLR case EUAC and the adaptation case EUAC for each adaptation method.

We assumed that discontinuous permafrost area will experience engineering construction problems due to permafrost settlement caused by temperature increases. We estimate that a climate warming could add about \$6 million annually to annual cost for Alaska roads in discontinuous permafrost areas from 2010 to 2050. Under the current temperature projection, permafrost settlements that are related to the climate warming will be the cause of the reduced service life of Alaska roads, hence increasing the annual cost for Alaska roads in discontinuous permafrost areas.

The EUAC of pre-thaw is about \$96 million; lower than CCSLR case EUAC (\$100 million but higher than ASLR case EUAC (\$94 million). These numbers do not mean that people in Alaska should pay this exact amount of money for each case because these numbers are only estimations, assuming that every road in discontinuous permafrost was built in 2010. These numbers are provided in order to address the possible economic size and to compare the relative size each other.

The EUACs of ACE and thermosyphone are \$108 million and \$483 million respectively, both of which is higher than the CCSLR case. Nevertheless, we conclude that ACE is still recommendable because the initial cost will decrease in areas where coarse rock is available (Doré, 2005). Therefore, the cost can be economically effective in these areas. In addition, since we had limited information, we simply assumed roughly that the ACE will decrease 30% of the maintenance cost used for the normal road. It might also be possible that the ACE will reduce the maintenance cost more than the assumption. Therefore, it is also likely that the ACE will be more cost effective. It seems that thermosyphon is not recommendable from an economic viewpoint.

However, our analysis is just simple cost comparison regardless of severity of permafrost degradation. Therefore, thermosyphon still can be used for the potential severe permafrost degradation regions.

We compared cost effectiveness of an adaptation method assuming that the chosen method will be used for all roads in discontinuous permafrost areas regardless of the severity of permafrost settlement. However, in practice, an adaptation method should be chosen considering the severity of permafrost settlement. Therefore, the effectiveness of total cost saving across Alaska owing to adaptation methods depends on how efficiently a chosen method works in a certain area.

The thermal analysis of the Alaska Highway monitoring site at Beaver Creek has shown that despite a cooling trend of average air temperatures over the 7-year monitoring period, soil temperatures beneath the embankment have increased steadily and significantly (Doré, 2005). Nevertheless, the permafrost degradation is likely to be amplified by climate related temperature increase. Considering the fact that the problem will worsen with the warming trend in the future, more effective adaptation methods are required to protect roads from permafrost settlement.

Nevertheless, these adaptation methods would not solve problems, but would only lessen damage costs that Alaska has to pay in the future. It is critical that adaptation methods are developed and implemented for new construction and major reconstruction as soon as possible, so that the infrastructure can withstand expected climate changes. Paying the cost for adaptation methods now may decrease infrastructure repair costs in the future.

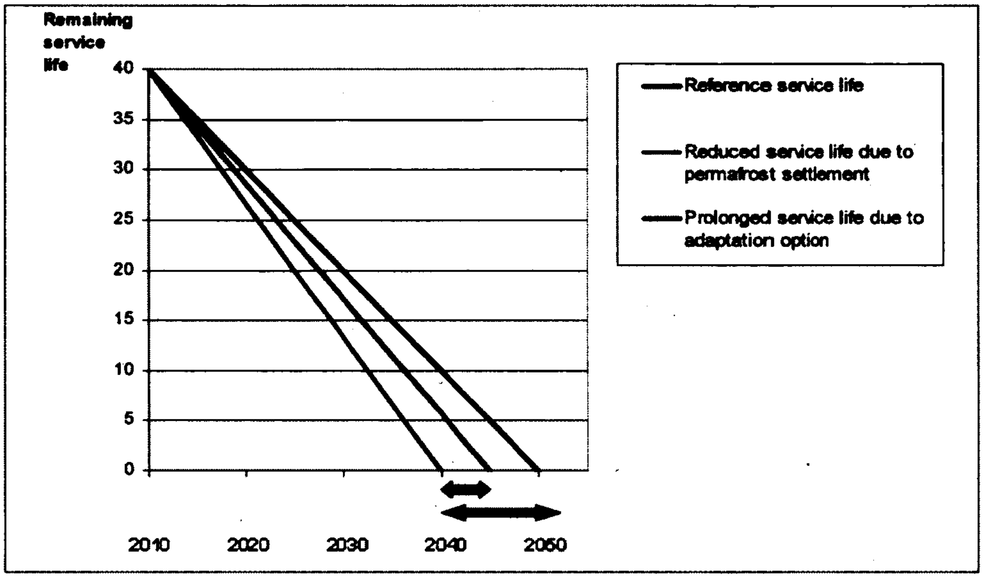

Figure 4.1 Concept of Reduced Service Life and Prolonged Service Life due to Adaptation.

Red block arrow represents service life difference between reference service life case and climate change case. This also means "reduced service life" due to permafrost settlement caused by climate warming. Green block arrow represents service life difference between climate change case and adaptation case and means "increased service life" based on climate warming case due to adaptation options.
Developed concept from Chapter 3

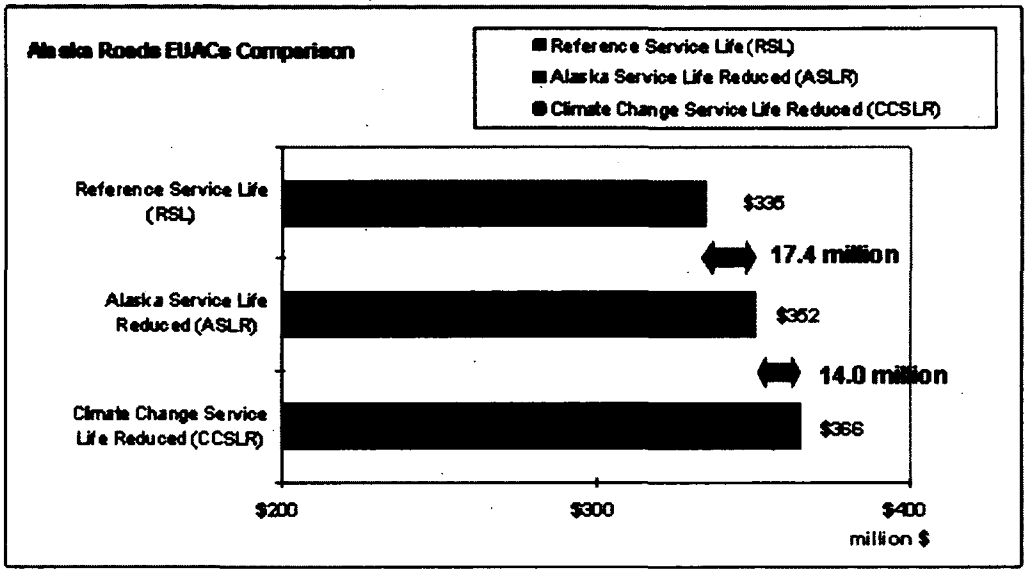

Figure 4.2 Alaska Road EUACs Comparision.

Each bar means the EUAC for identical Alaska roads under different cases. Blue block arrow represents the increased EUAC (annual cost) due to reduced service life of Alaska roads under Alaska condition. Red block arrow represents the increased EUAC (annual cost) due to additionally reduced service life of Alaska roads under the current temperature projection.

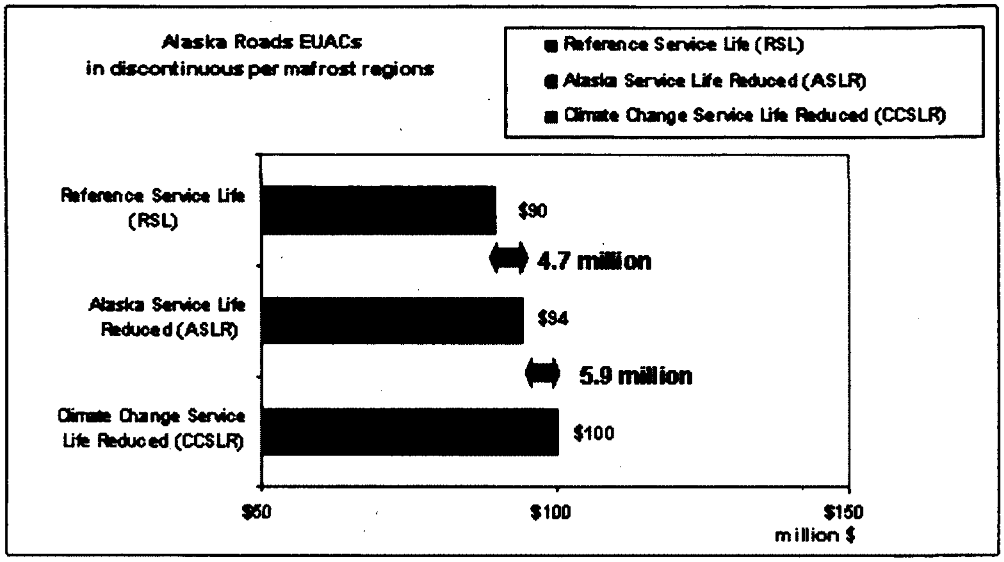

Figure 4.3 Alaska Roads in Discontinuous Permafrost Areas EUACs.

Each bar means the EUAC for identical Alaska roads in discontinuous permafrost regions under different cases. Blue block arrow represents the increased EUAC (annual cost) due to reduced service life of Alaska roads in discontinuous permafrost regions under Alaska condition. Red block arrow represents the increased EUAC (annual cost) due to additionally reduced service life of Alaska roads under climate change condition.

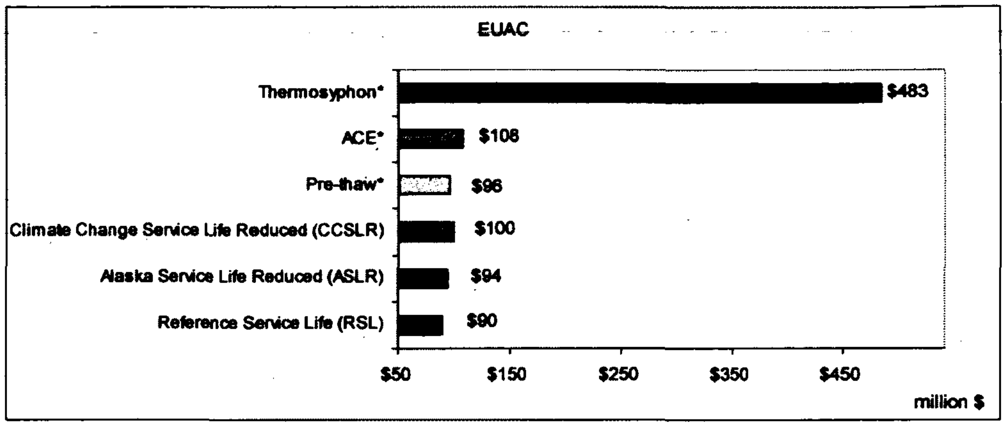

Figure 4.4 The EUACs of Each Case

* means the case of adaptation methods. Each column represents the EUAC (annual cost) of each case of Alaska roads. Pre-thaw is the only case that has a lower cost than that of the CCSLR case, which indicates that it can be an economically effective adaption option. The EUACs of ACE and thermosyphon are higher than that of the CCSLR case, making the methods not economically recommendable.

Table 4.1 Net installed Costs of Pre-Thaw Modes

Mode	In-place cost		Estimates	
	($/m^2)	($/yd*)	($/km)	($/mile)
Polyethylene film (.1 mm)	0.35	0.29	6,300	10,200
Polyethylene film (.15 mm)	0.47	0.39	8,500	13,700
Asphalt emulsion on gravel (2 litres/m^2)	0.96	0.80	17,500	28,200
Machine stripped	0.49	0.41	8,900	14,400
Hand cleared	0.62	0.52	11,400	18,300

Source: Esch (1982)

Table 4.2 Adaptation Method Cost Estimate

	Estimation year	Project	Distance used	Quantity	Unit price
ACE[1]	2004	Thompson Drive[3]	500m	4440 tons (US)	25$/ton (US)
Thermosyphon[1]	2004	Thompson Drive[3]	360m	150 each	3000$/each
Pre-thaw: Machine stripped[2]	1982	-	-	-	14,400$/mile

Source: [1] Doré (2005) [2] Esch (1982)

Note: [3] The original name of the road for this project is Loftus Road.

Table 4.3 EUACs for Alaska Road

	Total EUAC	Initial cost/mile	Annual O&M/mile	mile	Service life (year)	EUAC/mile
Reference Service Life (RSL)	$334,631,752	$303,220	$14,608	9564	20	$34,989
Alaska Service Life Reduced (ASLR)	$352,045,280	$303,220	$14,608	9564	16.7	$37,975
Climate Change Service Life Reduced (CCSLR)	$365,997,056	$303,220	$14,608	9564	differs by PSHI	differs by PSHI

Source: Data extracted from Chapter 3

Both the service life and EUAC/mile of each road in case of CCSLR model differ by PSHI because of it site specific PSHI.

Table 4.4 Results

		Total EUAC	Initial cost/mile	Annual O&M /mile	Service life (year)	EUAC/mile
Reference Service Life (RSL)		$89,752,092	$303,220	$14,608	20	$34,989
Alaska Service Life Reduced (ASLR)		$94,422,600	$303,220	$14,608	16.7	$36,809
Climate Change Service Life Reduced (CCSLR)		$100,316,869	$303,220	$14,608	Differ by each road	Differ by each road
Adaptation	Pre-thaw	$96,430,905	$336,167	$11,686	16.7	$37,592
	ACE	$108,087,999	$414,090	$10,225	16.7	$42,137
	Thermosyphon	$483,397,072	$2,331,590	$8,765	16.7	$188,446

4.7. References Cited

ACIA (2004) Impacts of a warming Arctic: Arctic climate impact assessment, Cambridge University Press.

ACIA (2005) Arctic climate impact assessment, Cambridge University Press.

Alaska Department of Transportation and Public Facilities (AKDOT&PF) (1993) Experimental feature work plan thermosyphons for permafrost preservation. Alaska Department of Transportation and Public Facilities (AKDOT), [online] Available from www.dot.state.ak.us/stwddes/research/assets/.../expfeat_ak_89_05.pdf [Accessed 9 Nov. 2011].

Cole, H., Colonell, V. & Esch, D. (1999) The economic impact and consequences of global climate change on Alaska's infrastructure, Assessing the Consequences of Climate Change for Alaska and the Bering Sea Region, Edited by Gunter Weller, Patricia A. Anderson, Fairbanks, USA, p.43-57.

Demo, G. P. (2006) Life cycle cost analysis and discount rate on pavements for the Colorado Department of Transportation. Colorado Department of Transportation.

Dessler, G., Starke, F. A. & Cyr, D. J. (2001) Management: Leading people and Organizations in the 21st Century, Upper Saddle River, NJ: Prentice Hall.

Doré, G. (2005) Research on the performance of the Beaver Creek section of the Alaska highway. Department of Highways and Public Works, Government of Yukon.

Esch, D. C. (1982) Thawing of permafrost by passive solar means. Proceedings, 4th Canadian Permafrost Conference.

Esch, D. C. (1988) Embankment case histories on permafrost. Embankment Design and Construction in Cold Regions. A. Phukan and W. H. Haas, American Society of Civil Engineers, p.127-159.

Fortier, R., LeBlanc, A.-M. & Yu, W. (2011) Impacts of permafrost degradation on a road embankment at Umiujaq in Nunavik (Quebec), Canada. Canadian Geotechnical Journal 48, 720-740.

Goering, D. J. (1998) Experimental investigation of air convection embankments for permafrost-resistant roadway design. Seventh International Conference. Collection Nordicana, No 55, Whitehorse, Canada, p.319-326.

Goering, D. J. (2004) Thompson drive to contain permafrost protection measures Alaska Business Monthly. Anchorage, Alaska Business Publishing Company.

Hoeve, T. E., Fuqun, Z. & Aining, Z. (2006) Potential Cost Impacts for Adaptation of Building Foundations in the Northwest Territories. EIC Climate Change Technology, 2006 IEEE.

Instanes, A. (2003) Climate change and possible impact on Arctic infrastructure. Permafrost: Proceedings of the Eighth International Conference on Permafrost. A.A. Balkema.

IPCC (2007) Climate change 2007 : the physical science basis : contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

ISO 15686-1 (2011) Buildings and constructed assets- Service life planning- Part 1: General principles and framework, International Standard Organisation, Geneva.

ISO 15686-2 (2001) Buildings and constructed assets- Service life planning - Part 2: Service life prediction procedures. ISO 15686-2:2001(E).

Jorgenson, M. T., Racine, C. H., Walters, J. C. & Osterkamp, T. E. (2001) Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change 48, 551-579.

Jorgenson, M. T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E. A. G., Kanevskiy, M. & Marchenko, S. (2010) Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 40, 1219-1236.

Maynard, B. (2007) Building On Thick Ice Alaska Business Monthly. Anchorage, Alaska Business Publishing Company

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2001) Subsidence risk from thawing permafrost - The threat to man-made structures across regions in the far north can be monitored. Nature 410, 889-890.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2002) Climate change and hazard zonation in the circum-Arctic permafrost regions. Natural Hazards 26, 203-225.

Newman, D. (2004) Fundamentals of engineering: FE exam preparation, Kaplan Publishing.

Noie, S. H. (2005) Heat transfer characteristics of a two-phase closed thermosyphon. Applied Thermal Engineering 25, 495-506.

Osterkamp, T. E., Esch, D. C. & Romanovsky, V. E. (1998) Permafrost, In: G. Weller and P.A. Anderson (Eds.) Implications of Global Change for Alaska and the Bering Sea Region, Proceedings of a Workshop, University of Alaska Fairbanks, 3–6 June.

Raupach, M. R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J. G., Klepper, G. & Field, C. B. (2007) Global and regional drivers of accelerating CO2 emissions. Proceedings of the National Academy of Sciences 104, 10288-10293.

Romanovsky, V. & Osterkamp, T. (2001) Permafrost: changes and impacts. In R. Paepe & V. Melnikov (Ed.) Permafrost response on economic development, environmental security and natural Resources. Dordrecht, Netherlands: Kluwer Academic Publishers, 297-315.

Saboundjian, S. (2008) Evaluation of alternative embankment construction methods. State of Alaska, Alaska Dept. of Transportation and Public Facilities.

Scenarios Network for Alaska and Arctic Planning (SNAP) (2012) Uncertainty. [online] Available from http://www.snap.uaf.edu/uncertainty.php [Accessed March 15, 2012].

Seifert, R. D. & University of Alaska Fairbanks Cooperative Extension Service (2007) Permafrost : a building problem in Alaska, Fairbanks, Cooperative Extension Service, University of Alaska Fairbanks. http://library.state.ak.us/asp/edocs/2007/03/ocm122264369.pdf.

Shur, Y. & Goering, D. (2009) Climate change and foundations of buildings in permafrost regions. Permafrost Soils, 251-260.

Smith, S. L., Burgess, M. & Geological Survey of Canada (2004) Sensitivity of permafrost to climate warming in Canada, Ontario, Geological Survey of Canada.

Stephane, H. (2009) Strategies to adapt to an uncertain climate change. Global Environmental Change 19, 240-247.

U.S. Arctic Research Commission Permafrost Task Force (2003) Climate change, permafrost, and impacts on civil infrastructure, Special Report 01-03, U.S. Arctic Research Commission, Arlington, Virginia.

Walsh, J. E., Chapman, W. L., Romanovsky, V., Christensen, J. H. & Stendel, M. (2008) Global climate model performance over Alaska and Greenland. Journal of Climate 21, 6156-6174.

Chapter 5 Conclusion

My research examined permafrost settlement hazard in Alaska, estimated damage costs of public infrastructure in Alaska, and reviewed three adaptation methods for Alaska roads to save damage costs in the future.

The following conclusions were reached.

5.1. Permafrost Settlement Hazard Index

Permafrost temperatures in many northern latitude areas have increased during the past few decades, and mean annual ground surface temperatures along a north– south transect in Alaska have increased since the 1960s. Increases in permafrost temperature may result in thaw settlement and significant problems for public infrastructure. Therefore, as the climate warms, I can also expect that risks of infrastructure failure by permafrost thaw may increase in many areas of Alaska.

I examined regions at risk from permafrost settlement in Alaska and evaluated the relationship between the permafrost settlement hazard and maintenance costs for Alaskan roads. In order to examine the correlation, I developed the Permafrost Settlement Hazard Index (PSHI) by analyzing anticipated climate warming and examining the ecological characteristics that regulate permafrost settlement. I found that the discontinuous permafrost region is at more risk due to permafrost settlement than other regions of Alaska. I also projected the future permafrost settlement risk in Alaska in 2050 using projected future temperature increases from published climate models. Results of our analysis indicate that the index values in northern Alaska will be higher based on projected temperature changes and the risk of permafrost settlement in northern Alaska will be more serious in the future than today.

I then linked the PSHI to the cost data for roads maintenance that the Alaska Department of Transportation and Public Facilities (AK DOT&PF) has used for permafrost settlement related activities. Tests of the relationship between PSHI and actual maintenance cost data revealed that the region with the higher permafrost hazard value has had higher road maintenance costs.

5.2. Estimation of Damage Costs

Current economic activities in the Arctic depend on infrastructure; industries such as mining, tourism and fisheries depend on limited transportation. Permafrost degradation affects the performance of infrastructure and increases in maintenance costs. I estimated damage costs of public infrastructure in Alaska caused by climate change from 2010 to 2050 with updated data and methodology.

The damage cost estimate due to permafrost settlement, which is attributable to temperature changes, was calculated using the Equivalent Uniform Annual Cost (EUAC) method. Also, I focused on the whole cost required during the life cycle of the infrastructure, through the Life Cycle Cost Analysis (LCCA).

Therefore, my results were presented as an annual cost which is required to build and maintain by the end of service life. To estimate EUACs, first of all, I estimated the reduced service life considering all factors proposed by the Factor Method, which affect the service life of infrastructure in Alaska, which I considered to be an Alaska Service Life Reduced (ASLR) scenario. Then, I estimated the reduced service life focusing on the effect of permafrost settlement in the future, which I considered to be a Climate Change Service Life Reduced (CCSLR) scenario. I obtained the difference between the CCSLR scenario case EUAC and the ASLR scenario EUAC. Therefore, I defined the damage cost as the increased EUAC caused by a reduced service life of public infrastructure, resulting from permafrost settlement that is attributable to temperature increases.

I conclude that with the current climate change projection, climate warming may add about $106 million annually from 2010 to 2050 to annual cost for public infrastructure. This number indicates that there will be substantial costs additionally to maintain and keep the infrastructure under the condition of current climate change projection.

5.3. Comparison of Cost Effectiveness of Adaptation Methods

Permafrost thaw and degradation in the Arctic caused by climate change has been anticipated to impact the Alaskan infrastructure. Thawing permafrost causes settlement and embankment instabilities, leading to premature failure of existing structures. Because Permafrost thawing also affects roads, numerous alternative construction methods to counter the effects of permafrost thawing have been used and tested by the Alaska Department of Transportation and Public Facilities.

I addressed problems related to thawing permafrost for Alaska roads in discontinuous permafrost regions, then investigated the best adaptation method for Alaska roads in discontinuous permafrost regions from the economic perspective. I defined the adaptation cost for infrastructure as the additional cost incurred for the use of the alternative construction methods to withstand climate warming in the future. I identified the most cost- effective adaptation method by comparing the climate change EUAC (which is CCSLR scenario in Chapter 4) with the adaptation case EUAC for pre-thaw method, Air-Cooled Embankments (ACE), and thermosyphon.

Pre-thaw method is considered to be the most cost effective method. The EUAC of ACE is higher than that of the climate change case, which means ACE is not recommendable from the economic perspective. However, I concluded that the use ACE is still promising depending on site places which have easy access to coarse rocks, because this may decrease the initial cost. Also, it might also be possible that the ACE in these areas would reduce the maintenance cost more than the assumption. Therefore, it is also likely that the ACE will be more cost effective.

Thermosyphon is considered to be the method which are generally not cost competitive. Nevertheless, thermosyphon may still be used only for the potential severe permafrost degradation regions.

5.4. Uncertainty

Through the whole dissertation, I assumed the climate warming trend will cause additional permafrost to thaw. Based on this assumption, I addressed the permafrost settlement hazard in Alaska. I developed a Permafrost Settlement Hazard Index (PSHI), which considers anticipated climate warming and ecological characteristics. Then, I estimated damage cost caused by climate warming induced permafrost settlement in the field of public infrastructure with the created PSHI.

The annual cost of constructing and maintaining the entire infrastructure in Alaska under the reference service life condition (RSL), is $1420 million. The total EUAC of the ASLR model is $1510 million. The EUAC of the CCSLR model was calculated by estimating a reduced service life adjusted to include effects of permafrost settlement attributable to climate change. The total EUAC of the CCSLR model is $1,617 million. As a result, by obtaining the difference between

ASLK EUAC and CCSLR EUAC, I concluded climate warming may add about $106 million (7.5% of the ASLR EUAC) annually from 2010 to 2050 to annual costs for public infrastructure. This $ 106 million does not mean that people in Alaska should pay this exact amount of money annually to cope with damages of public infrastructure because this number is only an estimation, assuming that every infrastructure was built in 2010. This number is provided in order to address the possible economic damage Alaska could suffer in the future and to grasp the relative size of damage cost caused by climate warming by comparing annual costs of public infrastructure with and without consideration of the impact of climate warming on public infrastructure.

As an estimate study of future damage cost, this study includes uncertainties. First and foremost, the greatest uncertainty lies in the climate model itself. Thus, it is possible that the uncertainty associated with projections of future climate change will change the estimated cost. In practice, the future PSHI in Alaska in 2050 was created using Scenarios Network for Alaska and Arctic Planning (SNAP) temperature projections based on the A1B IPCC scenario, the midrange emission scenario. However, as I already mentioned, the actual emissions trajectory since 2000 was close to the highest-emission scenario, A1FI (Raupach et al., 2007). This also indicates that the calculated PSHI may underestimate the impact of climate-induced permafrost settlement on infrastructure and this may also cause to underestimate the damage costs. Estimating damage costs with different IPCC scenarios will be an option to take the uncertainty associated with the climate model.

Second uncertainty lies in the weights I assigned when I created the PSHI. To verify our calculated PSHI results, I tested the result using alternative importance ratings for each pair of ecosystem variable within the same importance rank of variables (see Table 2.2). I set up the comparative judgment based on knowledge from references. However, a sensitivity analysis with different ratios of the weights by providing importance rank of variables will be an option to take this uncertainty.

In addition, there will be an uncertainty associated with the discount rate I used. The choice of an appropriate discount rate in climate change related damages has long been debated and there is no definitive answer, because it is a matter of an ethical judgment on the well-being of people in the future. Nevertheless, discount rate is one of the most decisive factors in estimating future costs. This uncertainty will be taken into account by estimating damage costs with different range of discount rates.

5.5. Synthesis

Warming permafrost and the associated increase in depth of the active layer could impact existing infrastructure (U.S. Arctic Research Commission Permafrost Task Force, 2003, Nelson et al., 2001, Romanovsky and Osterkamp, 2001, ACIA, 2005). Some researches have demonstrated that permafrost temperatures across the Arctic have increased during the past few decades and the depth of the active layer is also increasing in many regions (ACIA, 2004, Romanovsky and Osterkamp, 2001). Nevertheless, a recent study indicates that the depth of the active layer at the Alaskan North Slope is relatively stable since 1995 and a progressive increase in depth of the active layer during the last five years is shown only at a small number of sites in the Alaskan Interior (Callaghan et al., 2011). This explains that there is no considerable change in the depth of the active layer in Alaska except for limited number of sites in the Interior of Alaska.

The active layer is the top layer of soil which thaws in summer and refreezes in winter (Shur et al., 2005), and the active-layer depth is strictly climate dependent (Shur and Jorgenson, 2007). Precisely, the length of the thaw season and summer air temperature are major factors which influence the development of active layer during the summer (Zhang et al., 1997). The depth of active layer varies between years, and extremely warm years can result in greater increase in the depth of active layer. The depth of active layer has local variability, ranging from 20 cm to more than a meter (Shiklomanov and Nelson, 1999), and permafrost initially develops at the base of active-layer (typically 1–1.5m depth) (Shur and Jorgenson, 2007). However, the active layer is generally removed when a building or roads are constructed; therefore, it is the permafrost itself that thaws after constructing infrastructure, hence affecting the stability of infrastructure. This is why I focused on permafrost settlement and its impacts on infrastructure, not the change of active layer and its impact on infrastructure. Thus, it is more appropriate to consider the projection of permafrost stability than to focus on the active layer when considering the stability of infrastructure.

A recent study indicates that, according to permafrost models, driven by general circulation models (GCMs), an area of approximately 850 000 km^2 (equivalent to about 57% of the total area of Alaska) is projected to experience a widespread permafrost degradation (Callaghan et al., 2011). This includes the possibility that areas where either patch or isolated permafrost exist will completely disappear in addition to areas where thawing is still ongoing. This projection of permafrost degradation supports the importance of my researches for Alaska to withstand climate warming and permafrost settlement attributable to climate warming. First, by having state-based

Permafrost Settlement Hazard Index and its projection in the future (Chapter 2), Alaska can recognize vulnerable areas and their changes in the future. Secondly, Alaska can anticipate and mitigate damages and economic loss in the field of public infrastructure by knowing the relative size of damage cost caused by climate warming (Chapter 3). Finally, Alaska is expected to adapt to any future change with less cost by identifying the cost-effectiveness of the adaptation methods for Alaska roads as a case study (Chapter 4).

My dissertation research investigated the current and future permafrost settlement hazard and obtained a state-based PSHI map. Then I estimated the damage costs of public infrastructure in Alaska caused by climate change using the PSHI. Finally, I investigated the cost effectiveness of the adaptation methods for Alaska road to encounter the permafrost thawing and presented the most recommendable method in Alaska.

The primary question I aspired to answer when I began my dissertation research was: "Is discontinuous permafrost region more at risk from permafrost settlement?" I could assume roughly that the question is true because the reaction in discontinuous permafrost to temperature, which is only a few degrees below the freezing point, can be more crucial. However, I wanted to prove this hypothesis beyond the assumption. The statistical analysis proved the discontinuous permafrost region is more at risk from permafrost settlement.

Then next aspiring question was: "Has the region with high permafrost settlement hazard value (PSHI) required more maintenance costs?" I hypothesized this in order to identify the relationship between my calculated PSHI values and actual maintenance expenses. In particular, I focused on maintenance costs for public roads since only the road maintenance data was available in Alaska. The result of maintenance cost analysis showed that areas with high PSHI have required higher maintenance costs than the areas with low PSHI. Proofing the PSHI with actual data is new knowledge. This result was used as a basic assumption for Chapter 3 (estimation of damage costs) and Chapter 4 (comparison of adaptation methods).

Larsen et al. (2008) did preliminary research, estimating the future costs for Alaska public infrastructure at risk from the climate change. However, I updated the existing database and developed a methodology to estimate damage costs moving beyond the limitations of the preliminary study. The estimation in my study dealt with the whole cost required during the life cycle of the infrastructure, through the LCCA, while Larsen et al. (2008) considered only replacement costs. Larsen et al. (2008) set up assumptions about thaw settlement of facilities on permafrost for each permafrost area ultimately to draw the information of reduction in service life for two climatic variables (temperature and precipitation). However, I estimated the service life of the structures using the future PSHI by the Factor Method, instead of providing assumptions. Such an examining of the reduction in service life due to the increased PSHI attributable to climate warming is a new method. Instead of showing total cost from now to 2050, I presented results as annual costs which would be required annually to keep and maintain the existing Alaskan infrastructure by the end of service life. The result shows that climate change could add the sizable sum of additional money (an annual cost of $106 million) to maintain and keep the infrastructure under the condition of current climate change projection from 2010- 2050.

I designed Part 4 in order to identify the cost-effectiveness of adaptation methods for Alaska. Due to the data availability in Alaska, I had to focus only on roads. Nevertheless, through Part 4, I wanted to emphasize that appropriate adaptation methods could decrease the damage cost when the damage cost itself is unavoidable.

Although my research has contributed toward our understanding of the permafrost, permafrost settlement and its impacts on structures, the estimation is still not perfect because of limited information in Alaska. Therefore, for the better estimation, detailed information on infrastructure type, cost components and adaptation methods will be necessary.

I believe my dissertation research has established a starting point toward understanding permafrost settlement impact, future damage cost and adaptation method to future damage that will possibly occur in Alaska. In addition, this study shows a new approach of estimating the reduced service life of structures and estimating damage costs. Applying the PSHI to economic and planning issue is new approach.

Nelson et al. (2001) provide a geographic overview of the hazard potential associated with permafrost thaw in the Arctic. In addition, there is a study which describes the development of cost estimates to adapt the existing building foundations of infrastructure in Northwestern Canada to climate change impacts (Hoeve et al., 2006). Nevertheless, there were limited studies both on permafrost settlement hazard in Alaska and on adaptation for existing infrastructures in Alaska to climate change impacts.

Therefore, I believe my dissertation research will contribute to establishment of the Alaska study in this research field.

5.6. Directions for Future Research

In part 2, the relationship between the PSHI and maintenance costs of the public infrastructure was evaluated in order to recognize the impact of climate-induced permafrost on maintenance cost. Due to limited data available for Alaska's infrastructure maintenance costs, however, I limited my analysis to the maintenance cost for public roads only. To examine this relationship, I obtained the annual maintenance expenditure data with mile-point information for the years 2005 through 2010 from AK DOT&PF. Although I proved the hypothesis that areas with high PSHI require greater maintenance cost, more detailed information on the relationship between the PSHI and maintenance costs of the public infrastructure could be collected by examining the relationship with cost data of the other infrastructure types.

The PSHI projection, which is used to estimate the reduced service life of infrastructure, is created with the limited map. As I already pointed out in Part 2, there will be more variables which affect permafrost settlement in nature. Therefore, the inclusion of projected change in other variables will strengthen the PSHI. For example, an inclusion of groundwater or drainage as variables in PSHI would strengthen the PSHI result. In addition, I considered temperature as the only independent factor which causes the service life of infrastructure to be reduced, because there is limited study on the effect of precipitation on permafrost settlement. However, by adding precipitation as a variable in PSHI, a future study may include better implication on the change of permafrost settlement in the future.

In part 3, I developed the database and methodology moving beyond limitations of the Larsen et al. (2008)'s study. First, I updated the existing Alaska Public Infrastructure Database established by Larsen et al. (2008), including three additional infrastructure categories (post office, library, and the University of Alaska). Nevertheless, infrastructures in Alaska were covered only partially: for example, I excluded Alaska railroads and telephone lines from the original database because of limited data on railroads and telephone lines cost components (e.g. construction cost, annual maintenance cost). Also, my estimates are limited to public infrastructure due to difficulty in collecting private sector data about infrastructure although private infrastructure, such as pipelines, underground cables, etc. is also affected by climate warming. Therefore, more comprehensive and thorough damage cost analysis will be attained by the inclusion of the excluded public infrastructure and private infrastructure.

As I have already mentioned, this study includes uncertainties as a future estimation study. As an alternative to address uncertainty, future study should be developed along with a sensitivity analysis. Suggesting parameters for the sensitivity are climate change projection, PSHI weights, and discount rate. The sensitivity analysis will test the response of output data with respect to input parameters. It is also expected to provide decision-makers with practical information about decisive factors to the increasing damage cost.

5.7. References Cited

ACIA (2004) Impacts of a warming Arctic: Arctic climate impact assessment, Cambridge University Press.

ACIA (2005) Arctic climate impact assessment, Cambridge University Press.

Callaghan, T. V., Johansson, M., Anisimov, O., Christiansen, H. H., Instanes, A., Romanovsky, V. & Smith, S. (2011) Chapter 5: Changing permafrost and its impacts. Snow, Water, Ice and Permafrost in the Arctic (SWIPA), Arctic Monitoring and Assessment Programme (AMAP), Oslo.

Hoeve, T. E., Fuqun, Z. & Aining, Z. (2006) Potential cost impacts for adaptation of building foundations in the northwest territories. EIC Climate Change Technology, 2006 IEEE.

Nelson, F. E., Anisimov, O. A. & Shiklomanov, N. I. (2001) Subsidence risk from thawing permafrost - The threat to man-made structures across regions in the far north can be monitored. Nature 410, 889-890.

Raupach, M. R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J. G., Klepper, G. & Field, C. B. (2007) Global and regional drivers of accelerating CO2 emissions. Proceedings of the National Academy of Sciences 104, 10288-10293.

Romanovsky, V. & Osterkamp, T. (2001) Permafrost: changes and impacts. In R. Paepe & V. Melnikov (Ed.) Permafrost response on economic development, environmental security and natural Resources. Dordrecht, Netherlands: Kluwer Academic Publishers, 297-315.

Shiklomanov, N. I. & Nelson, F. E. (1999) Analytic representation of the active layer thickness field, Kuparuk River Basin, Alaska. Ecological Modelling 123, 105-125.

Shur, Y., Hinkel, K. M. & Nelson, F. E. (2005) The transient layer: implications for geocryology and climate-change science. Permafrost and Periglacial Processes 16, 5-17.

Shur, Y. L. & Jorgenson, M. T. (2007) Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes 18, 7-19.

U.S. Arctic Research Commission Permafrost Task Force (2003) Climate change, permafrost, and impacts on civil infrastructure, Special Report 01-03, U.S. Arctic Research Commission, Arlington, Virginia.

Zhang, T., Osterkamp, T. E. & Stamnes, K. (1997) Effects of climate on the active layer and permafrost on the north slope of Alaska, USA. Permafrost and Periglacial Processes 8, 45-67.